Encapsulated MEMS Resonators : How the Package Enabled the Product

Bongsang Kim, Renata Melamud, Rob Candler, Matt Hopcroft, Jim Salvia, Shingo Yoneoka, Andrew Graham, Matt MessanaEldwin Ng, HyungKyu Lee, Shasha Wang, Chae-Hyuck Ahn, Vu Hong and Thomas Kenny
Department of Mechanical Engineering, Stanford University,
Stanford, CA, USA(E-mail:Kenny@cdr.Stanford.edu)

Aaron Partridge, Markus Lutz, Gary O’Brien, Gary Yama
Bosch Research and Technology Center, Palo Alto, CA

Resonators have been studied for Decades!

IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. ED-14, NO. 3, MARCH 1967

The Resonant Gate Transistor

HARVEY C. NATHANSON, MEMBER, IEEE, WILLIAM E. NEWELL, SENIOR MEMBER, IEEE, ROBERT A. WICKSTROM, AND JOHN RANSFORD DAVIS, JR., MEMBER, IEEE

NATHANSON ET AL.: RESONANT GATE TRANSISTOR

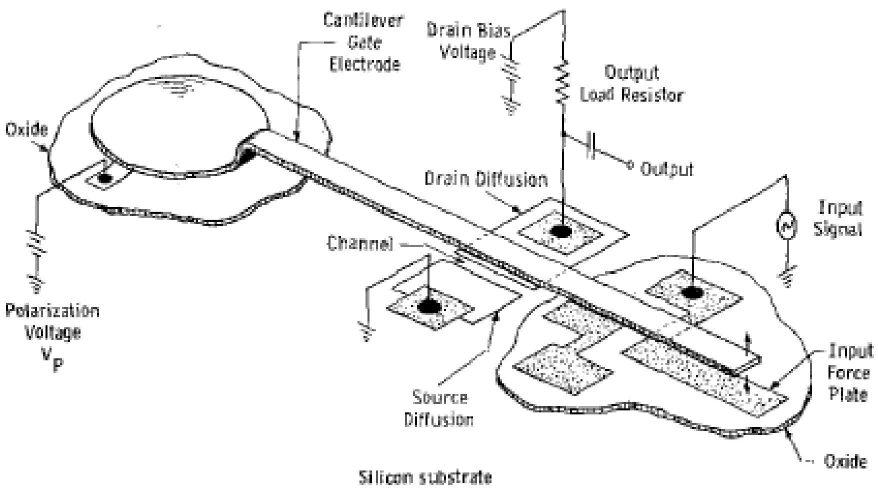
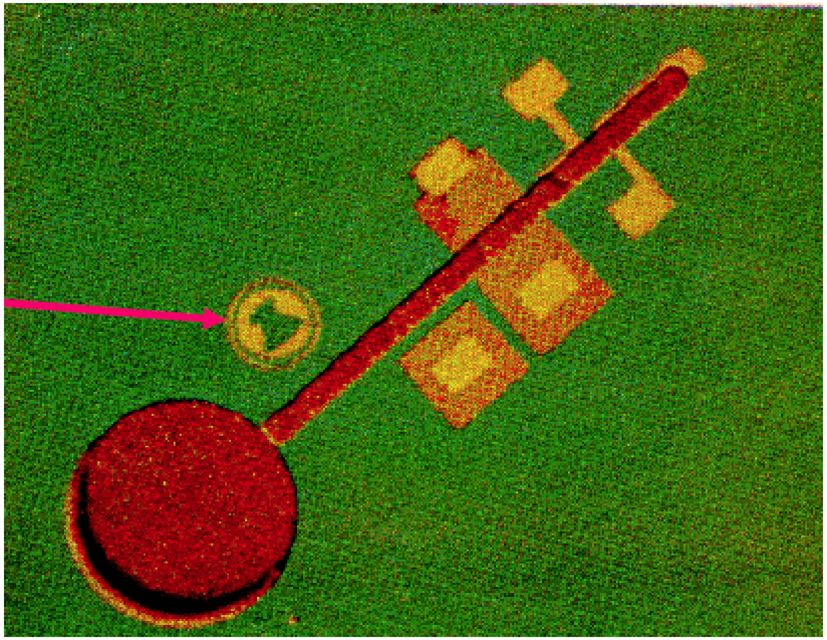
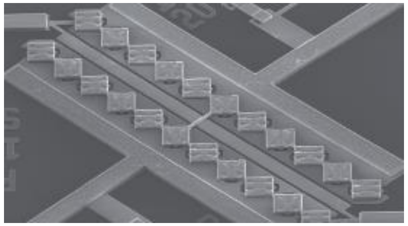


Fig. 1. Geometry and circuit connections of an RGT with a C-F resonant beam.

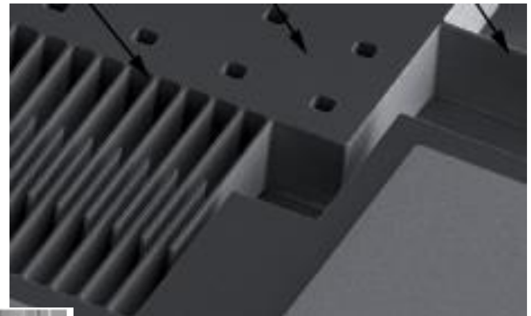


Electronics, Sept. 20, 1965 (cover)

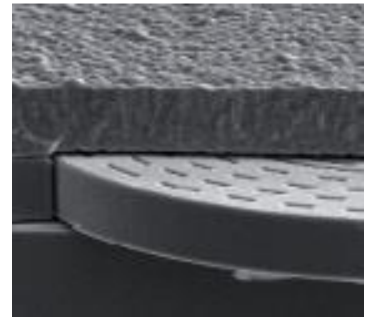
Resonators have been studied for Decades!



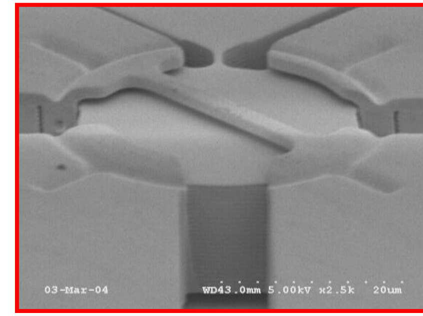
Nguyen, UCB



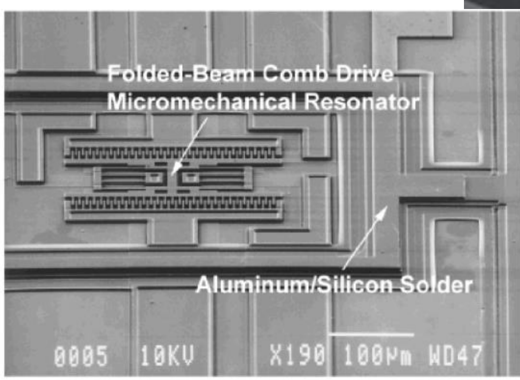
Paul, U. Freiburg



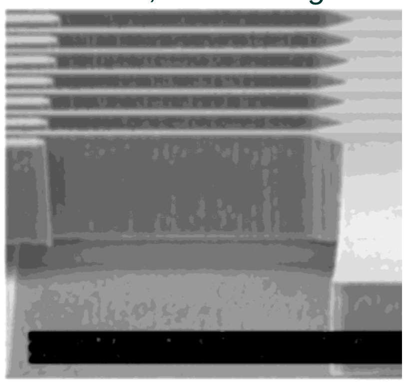
Lutz, SiTime



Pourkamali, Ayazi,



Cheng, Hsu, Lin, Nguyen, Najafi
U. Michigan, UC Berkeley



Kim, Lee, Lee, Sun,
Seoul National

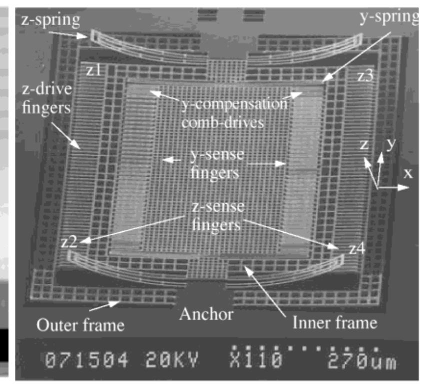
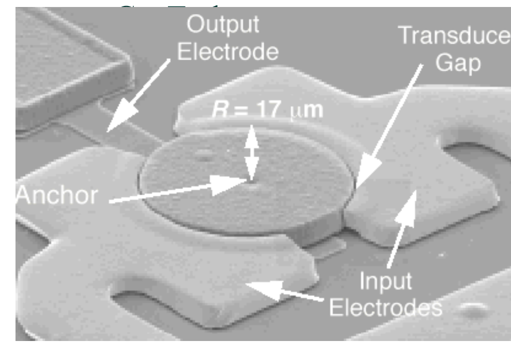
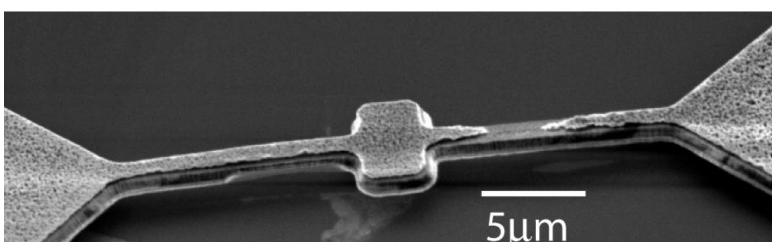


Figure 6: SEM of a released gyroscope.
Xie, Fedder, CMU



Hsu, Clark, Nguyen, U Michigan



Carter, Kang, White, Duwel,
Draper Labs

Many Recent Devices, Exciting Results, but No Serious Products

Is Packaging a Barrier to MEMS Adoption?

cost and development time

- packaging adds a lot of cost and time to MEMS products.

reliability

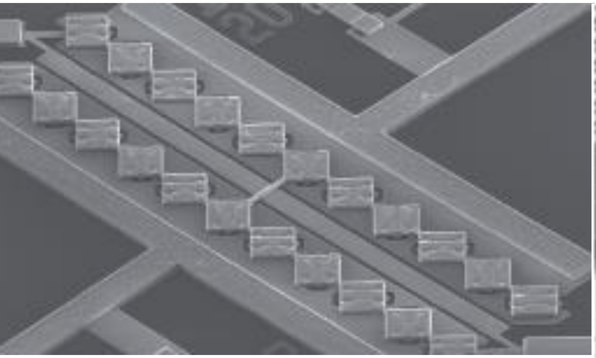
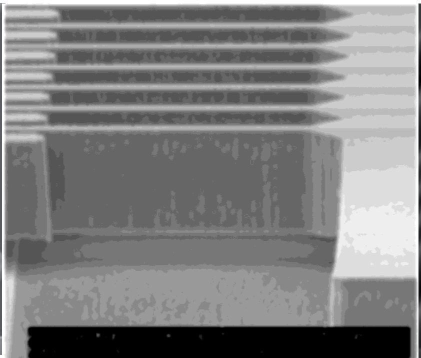
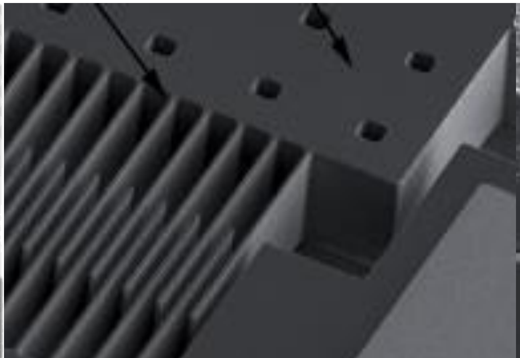
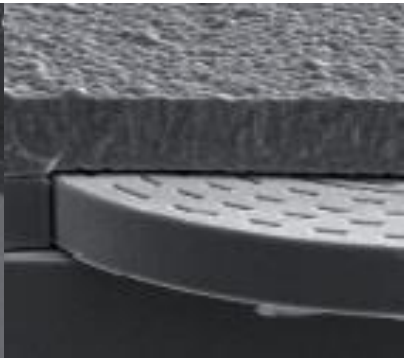
- packages can improve reliability.

lack of standard processes, universal foundries

- all MEMS devices require custom packages – nothing is standard

marginal or poor performance

- better packaging can allow device optimization for performance.

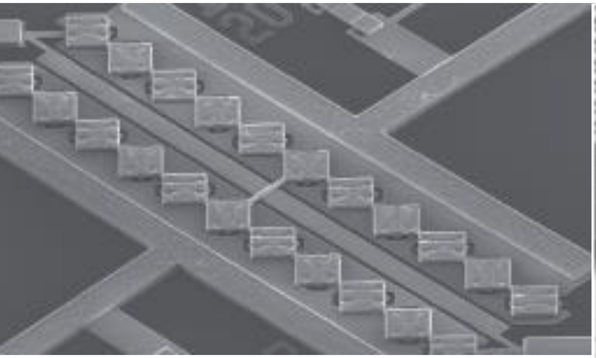
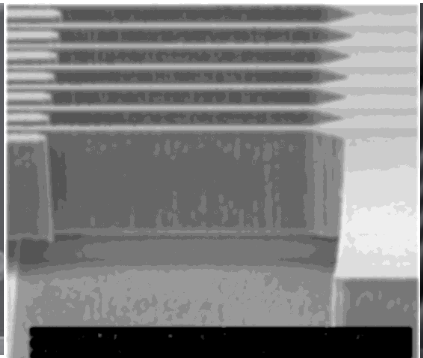
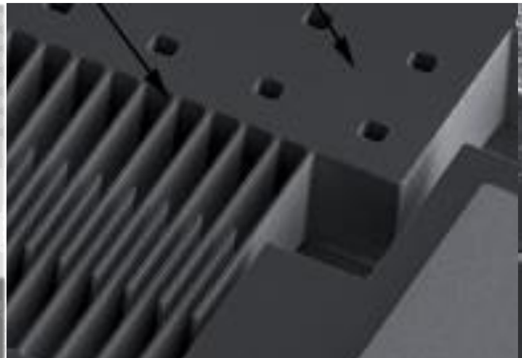
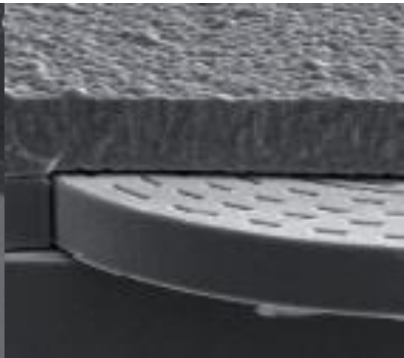
Reliability in MEMS Resonators

MEMS Resonators Suffer from Drift

- Adsorption/Desorption of Molecules
- Evolution/Aging of the Resonating Structure
- Failure of Hermetic Seals
- Mechanical Stress Relaxation
- Temperature Coefficient of Frequency (TCF)

MEMS Resonators can Fail

- Contact with Surrounding Structure
- Catastrophic Failure of Package

MEMS Packaging Example

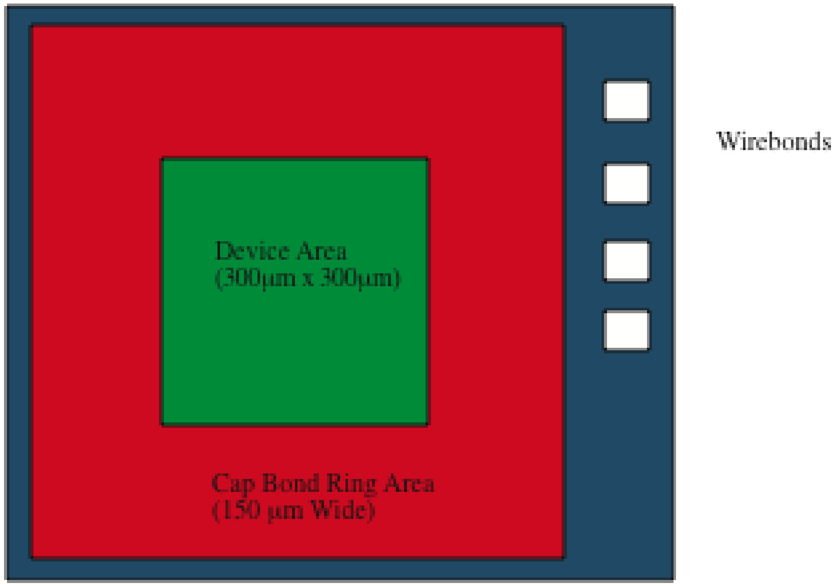
Fabricate MEMS, Release MEMS, Bonded Cap Package

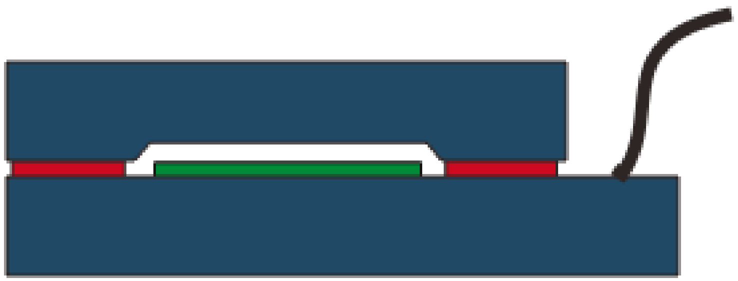
This approach is widely used in industry, but suffers from significant disadvantages.

- Lost Die space
- Yield
- Temperature budget
- Cost

Device <20% of Die,

Bond Ring is 60% of Die

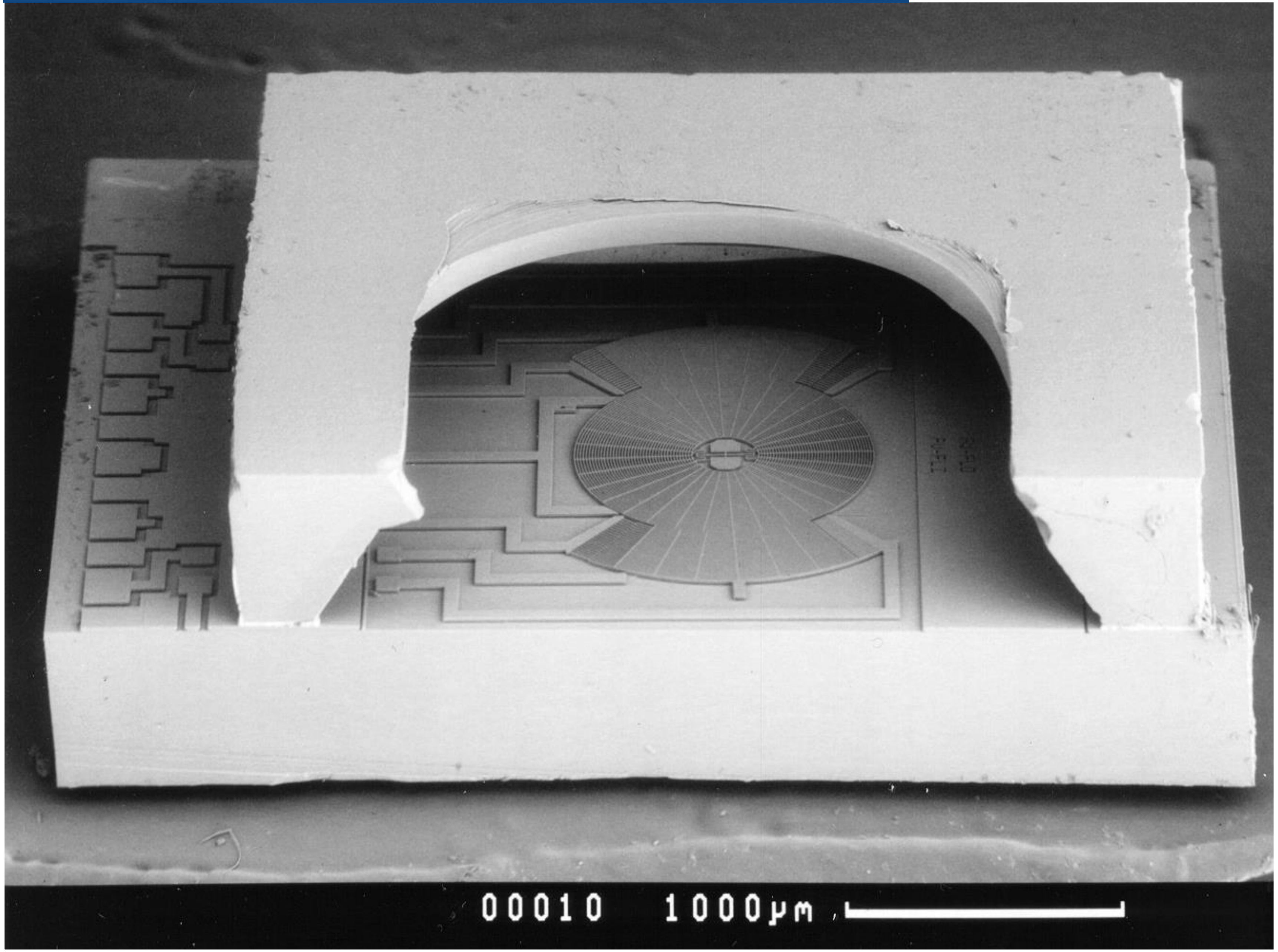




BOSCH

Early (1999) Example Production Yaw Rate Sensor

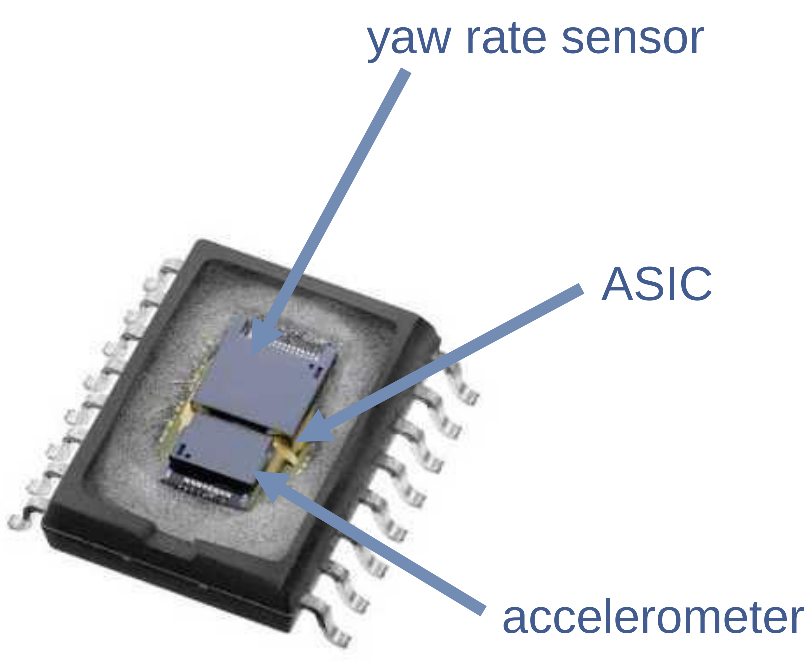
BOSCH



Biggest Markets want Smallest Packages

Bosch Multi-Sensor Example : SMI540

– *world's first* ESP combi-inertial sensor (yaw rate and acceleration) in mold-package



The dimensions of these products are approaching the dimensions of bonded-cap Sensor Elements.

The MEMS is actually only about 1% of the thickness of substrate and package.

MEMS is a Packaging Technology

Our Focus:

Turn the "problem" into an opportunity

MEMS includes many tools for making packages (vias, bonds, getters,…).

MEMS Designers should design devices that are Package-Ready

STANFORD UNIVERSITY

BOSCH

MEMS is a Packaging Technology

We propose:

Fabricate Device and Package Together.

Compromise Required : Constraints on devices

Opportunity Gained : Good packages can improve devices

Simplicity : Packaged MEMS can be handled, inserted, sold

STANFORD UNIVERSITY

BOSCH

Epi-Poly Encapsulation Process Development

Proposed in 2000 by Markus Lutz, shortly after arrival at opening of Bosch RTC.

- Initial Description on Scraps of Paper
- Objective was Miniaturization of Inertial Sensors for Automotive Applications
- Initial Effort Began Immediately
- Process development MUST be compatible with Bosch Production Fabrication Facilities in Germany.

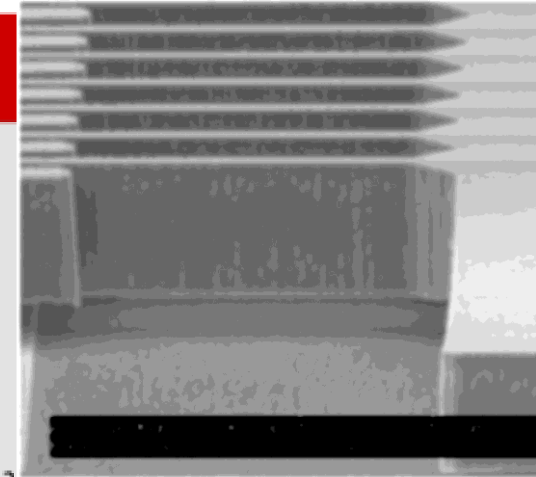
- Objective – Encapsulate the Minimum Volume for the minimally-sized inertial sensor chip.

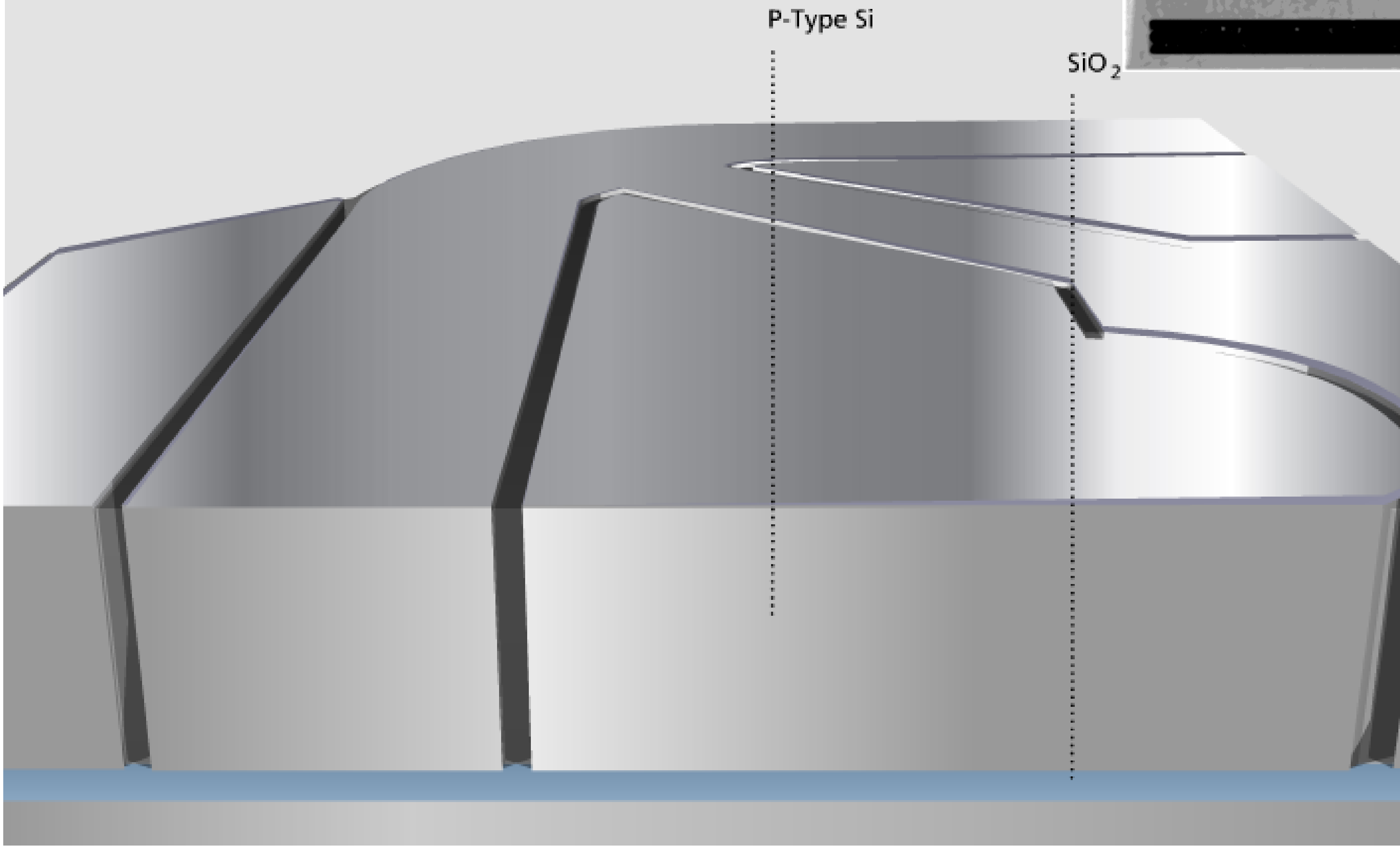
- **This was all about COST at the start…**

BOSCH

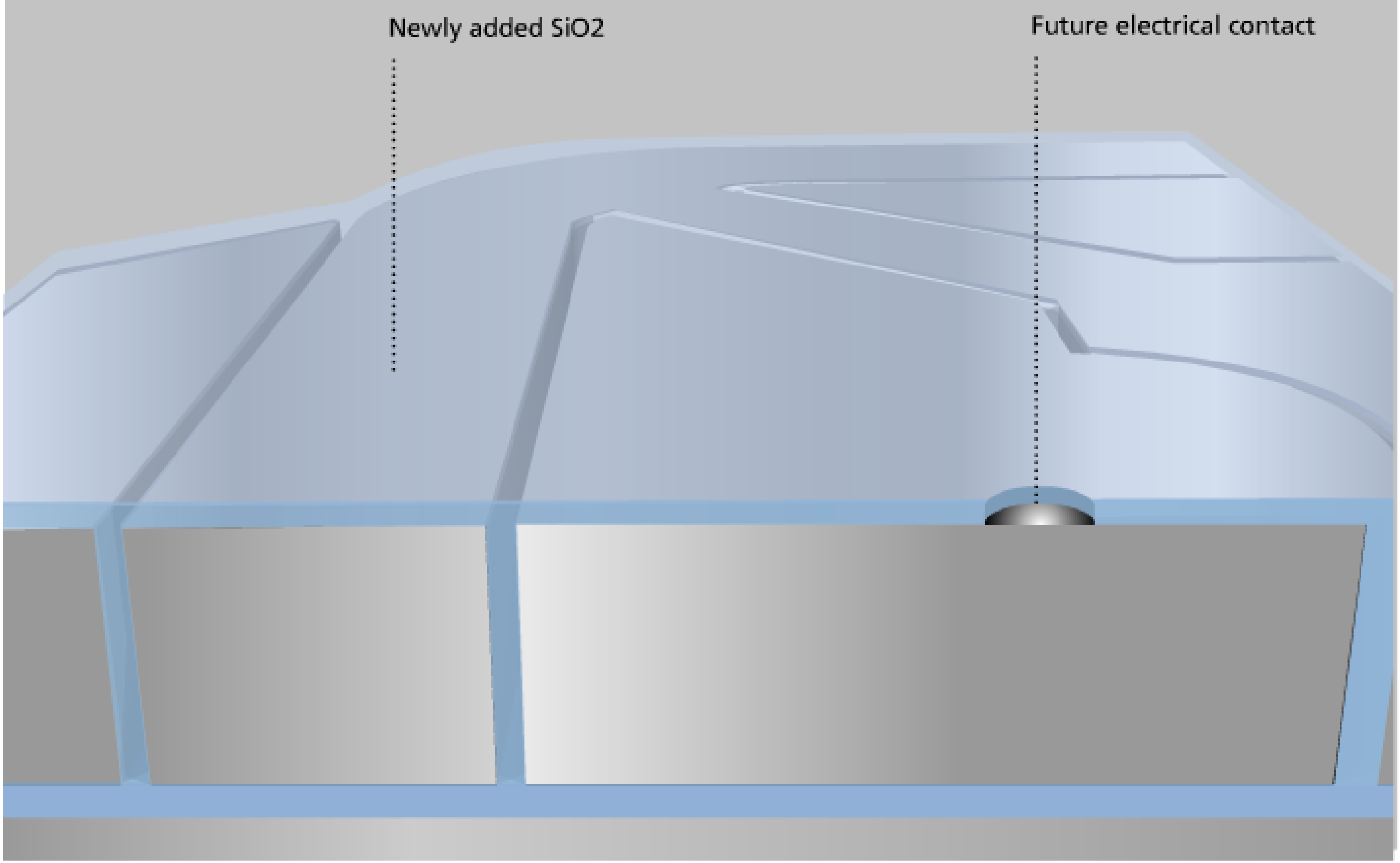
Trench formed with DRIE Technology developed by Robert Bosch

Trench Etch Device Geometry



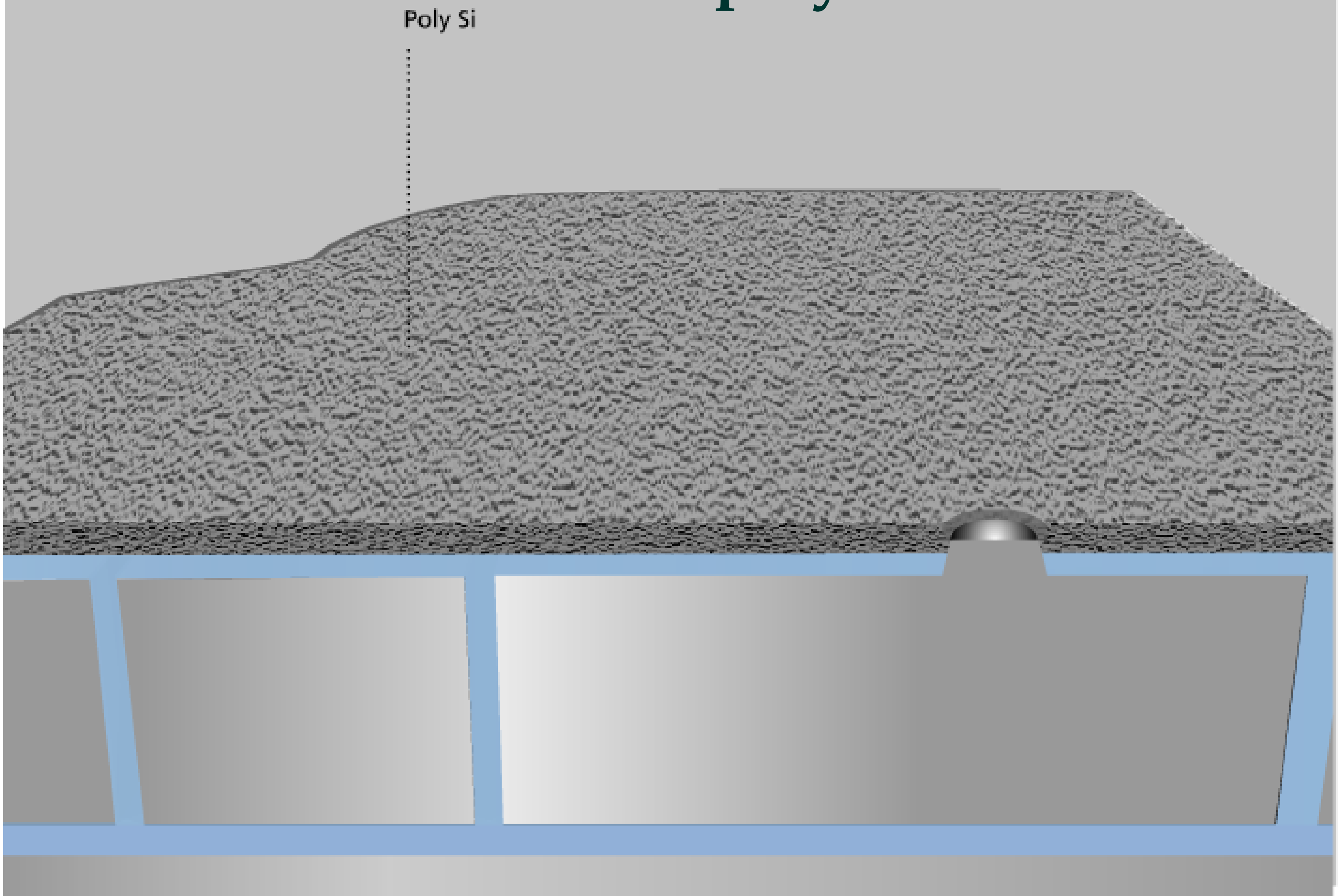


Grow Sacrificial Oxide

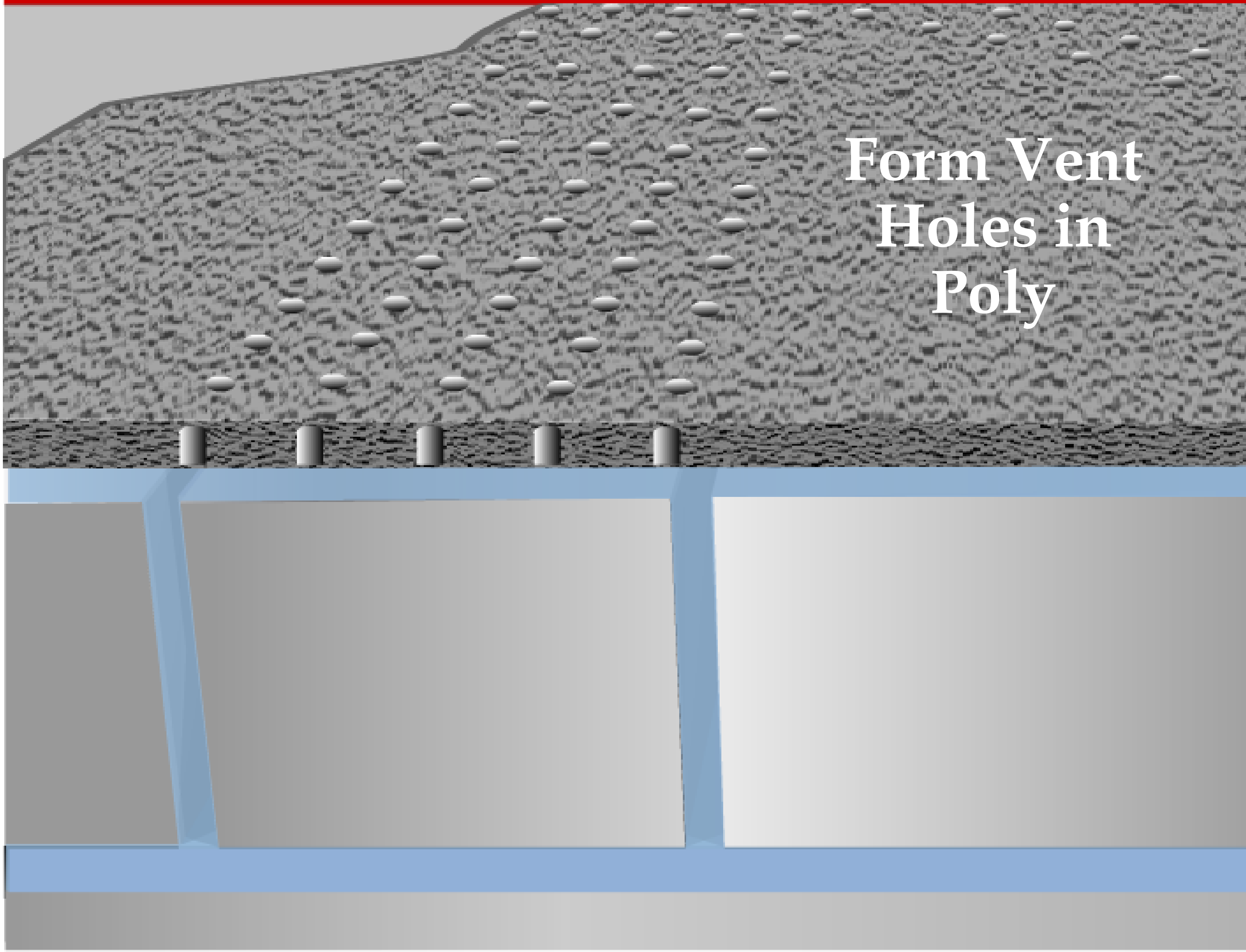


Poly Silicon Vent Layer Grown in Epi Reactor

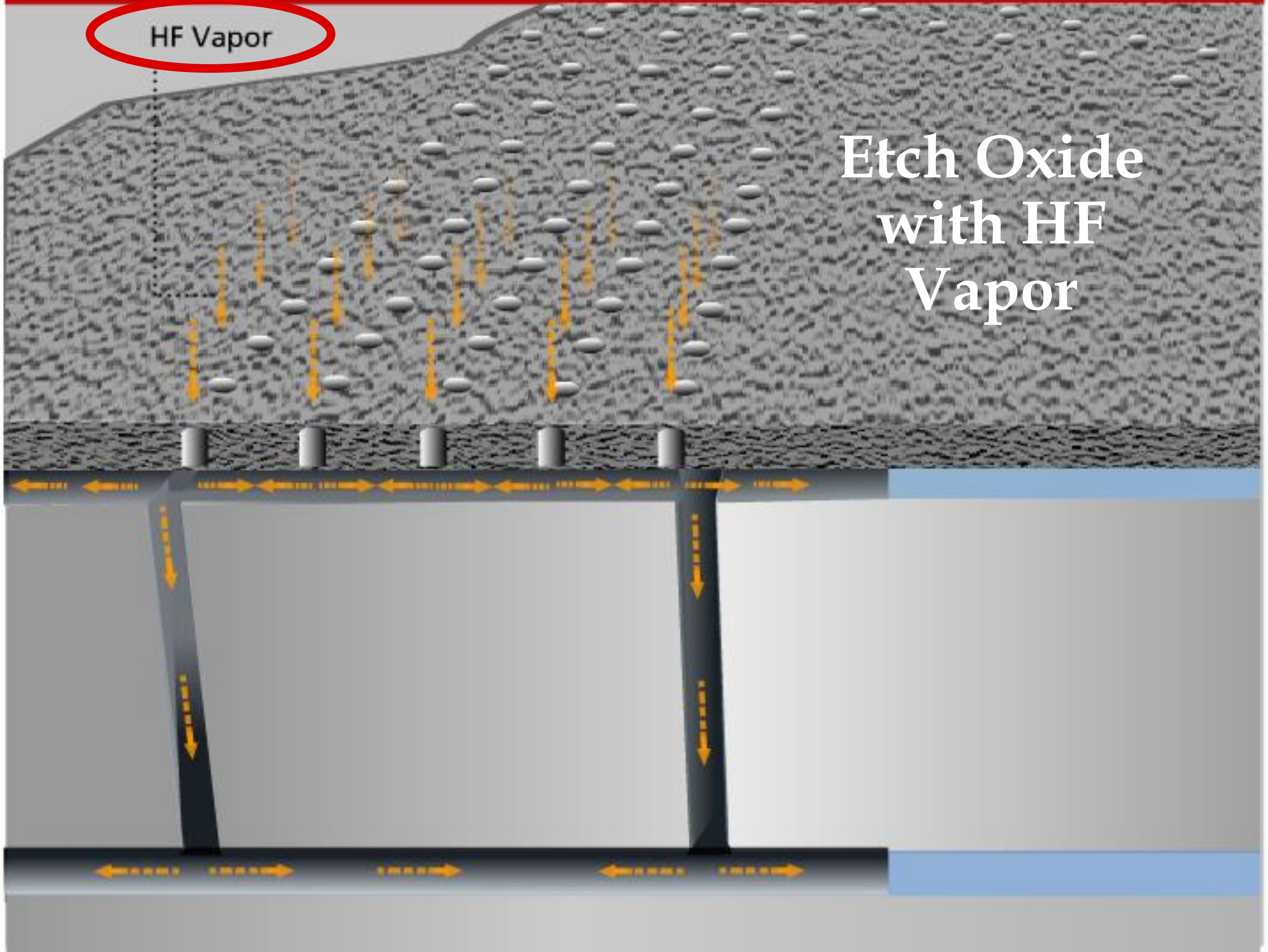
Cover with thin poly-Si



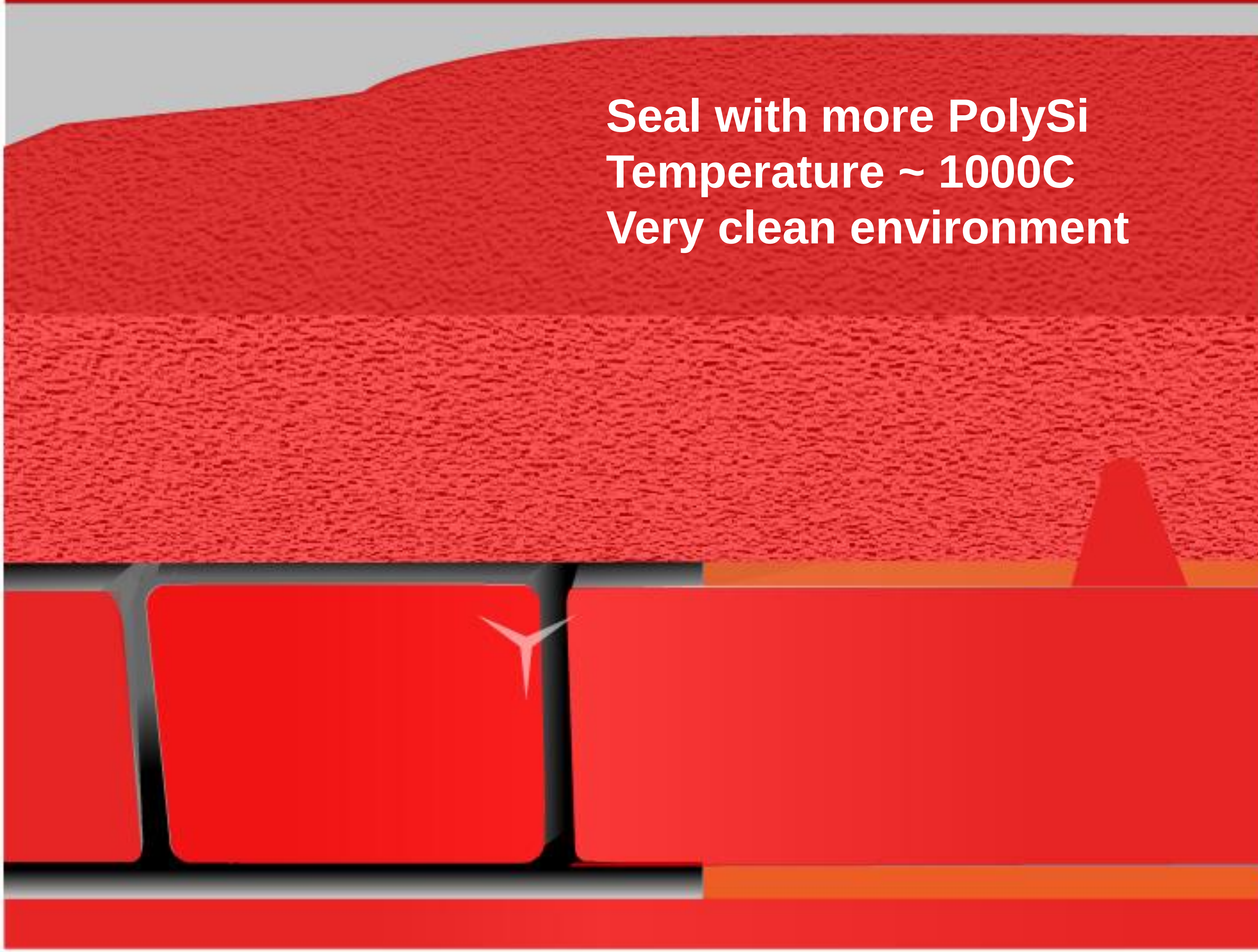
HF Vent Holes



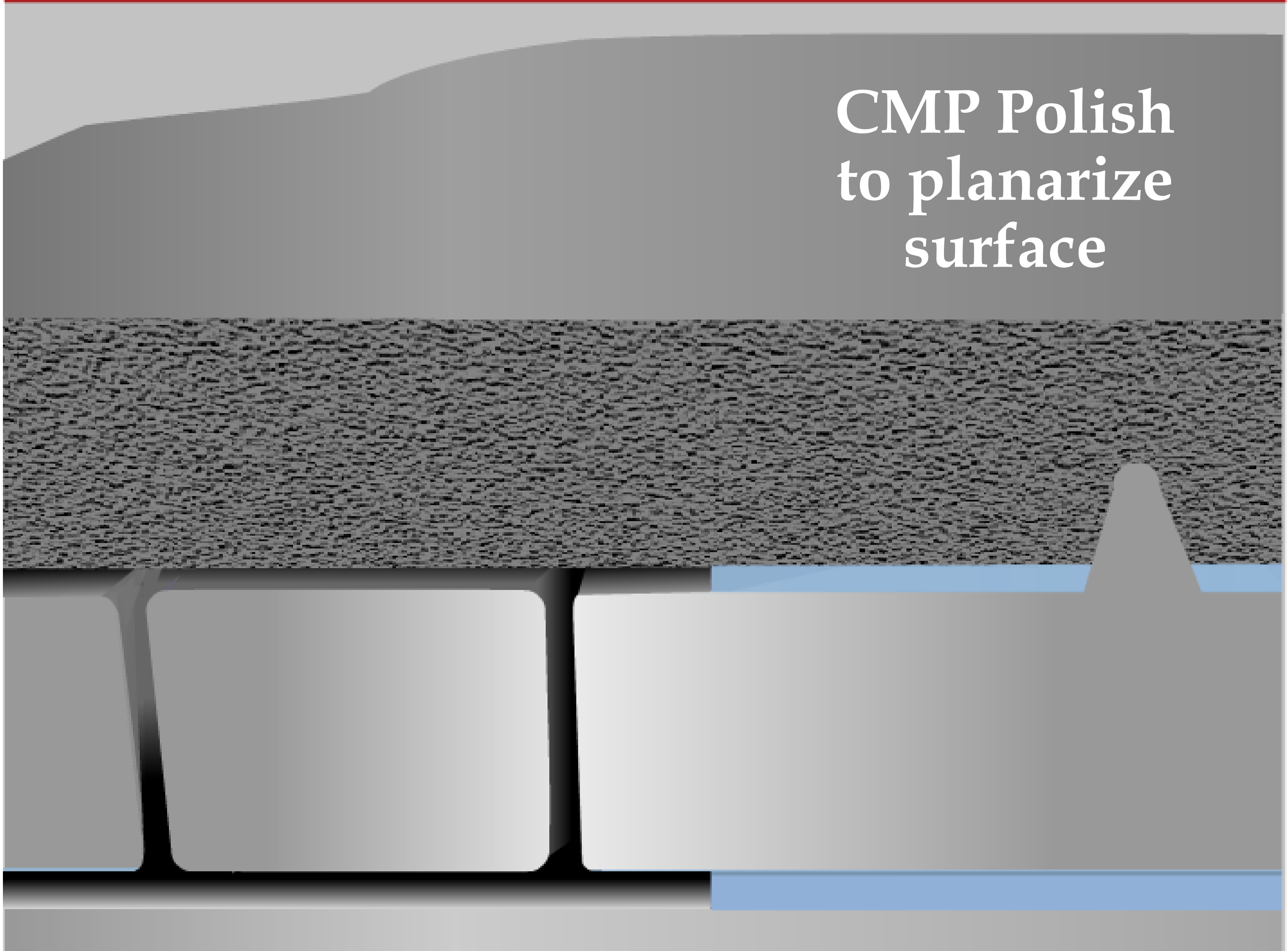
Resonator Release



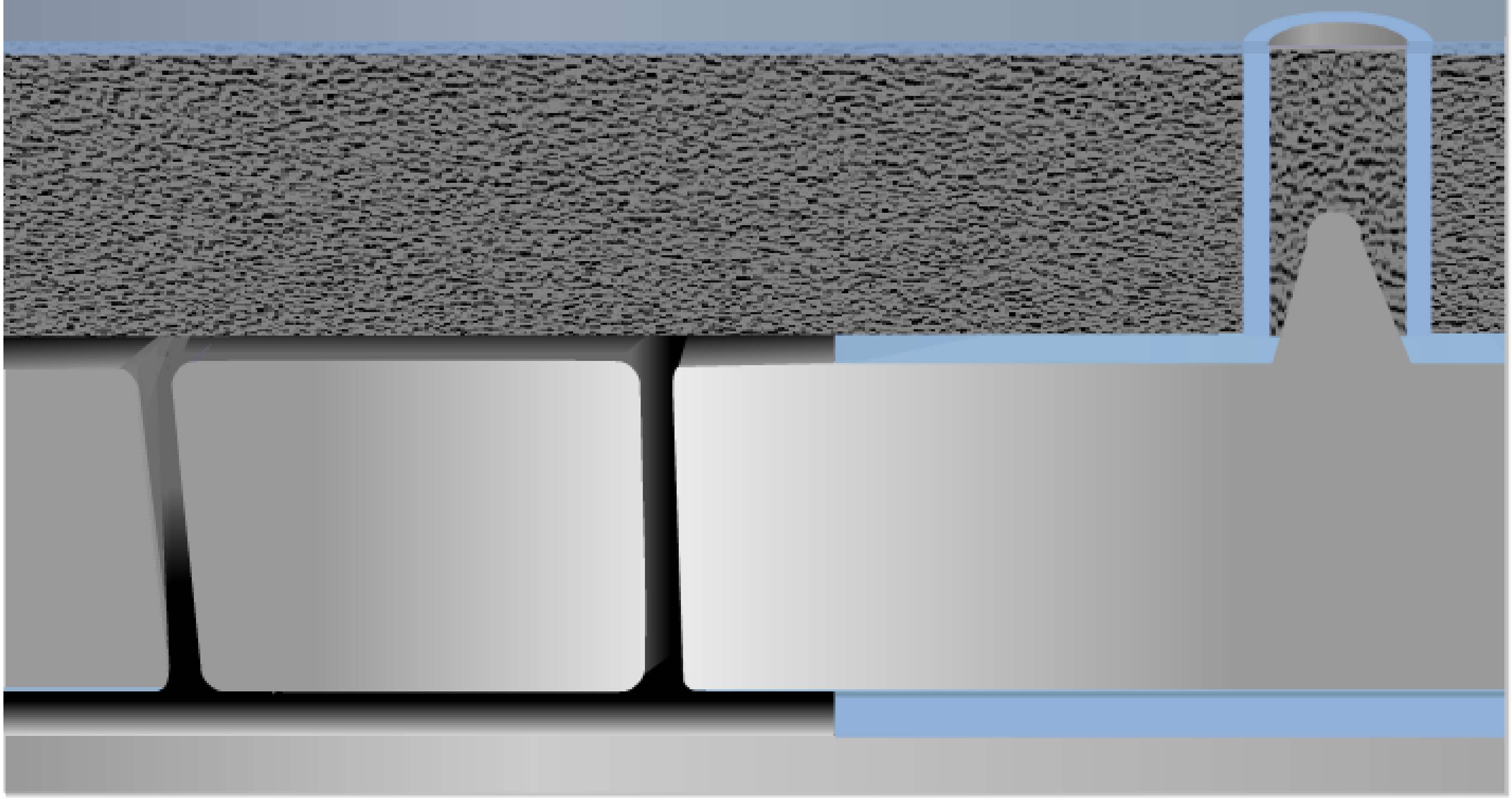
Epi Encapsulation



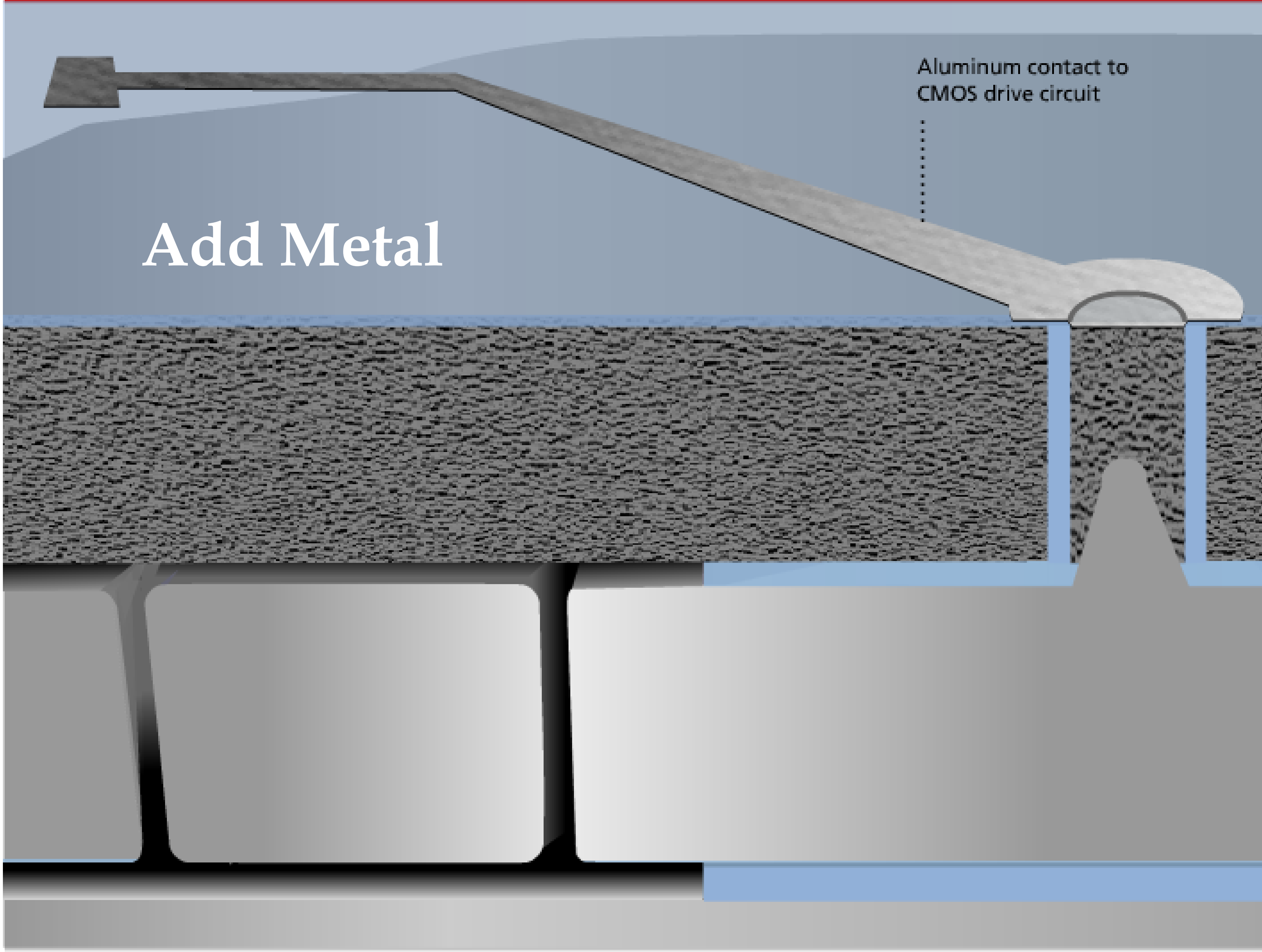
Polish



Etch and Fill Via Isolation



Metal Contacts



Wafer-Scale Package

Encapsulation Features

Small Footprint

- Maximize the # of Die/Wafer

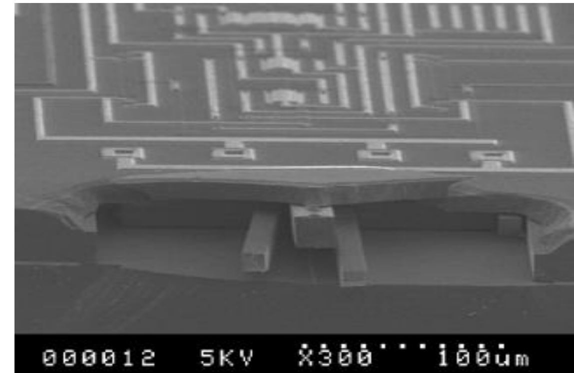
High-Temperature Seal (1000C)

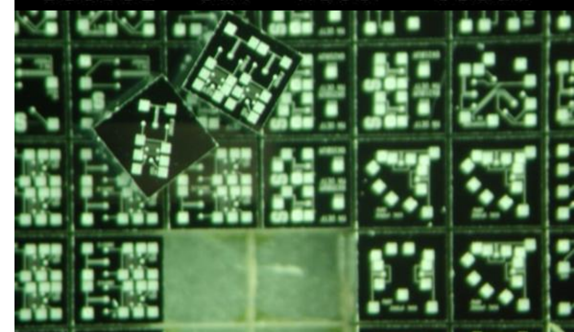
- Ultra Clean Process
- No Getter Required
- CMOS Compatible

Compatible with Standard Electronics Packaging

- No custom packaging
- Injection-molded package possible
- Allows use of existing packaging vendors

Useful for Resonators, Gyros, Accelerometers

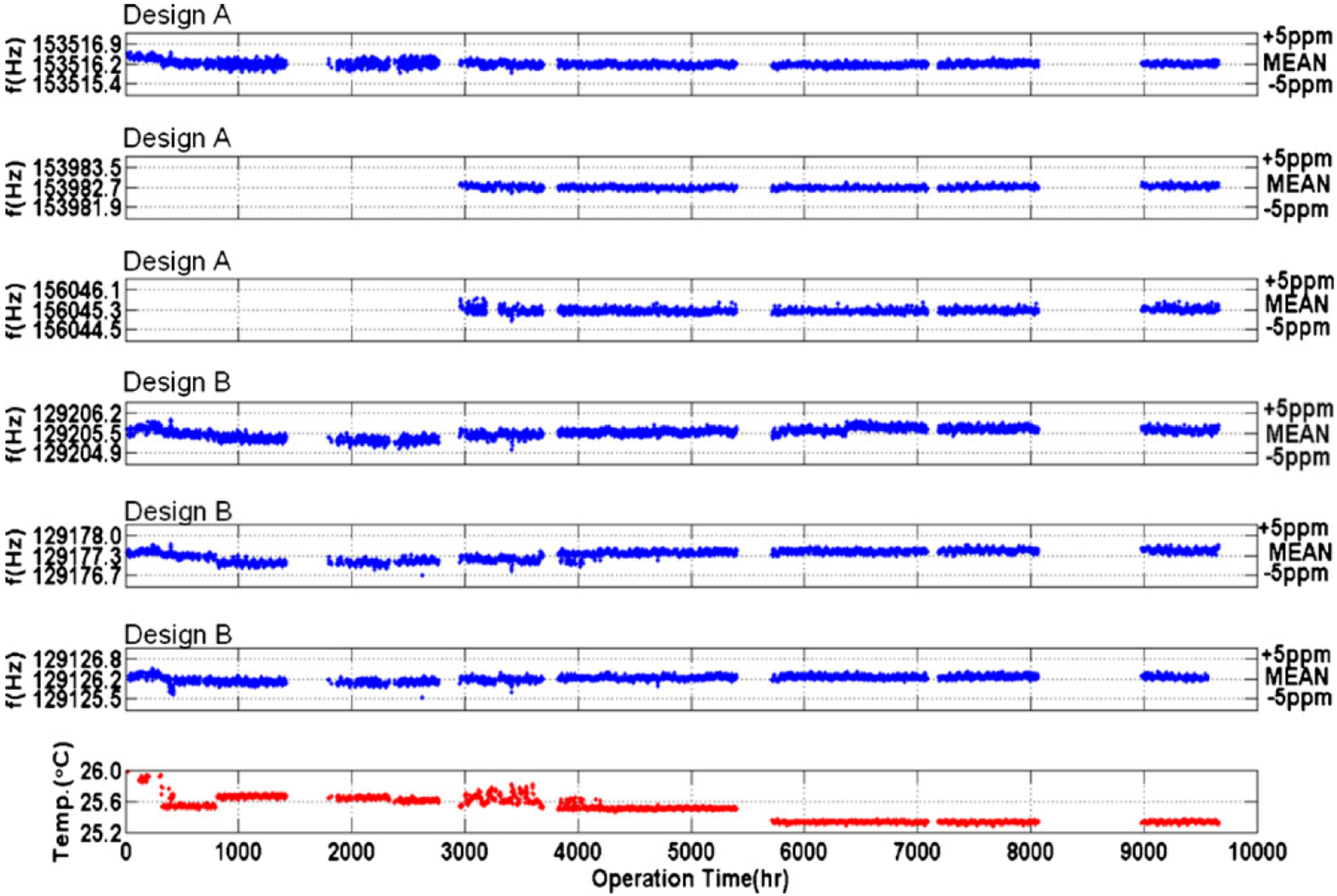




STANFORD UNIVERSITY

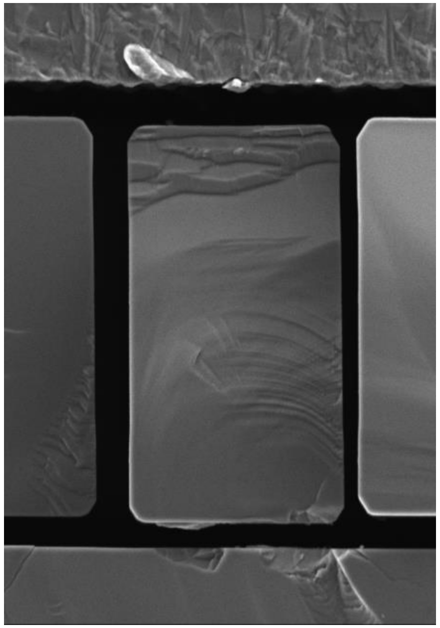
BOSCH

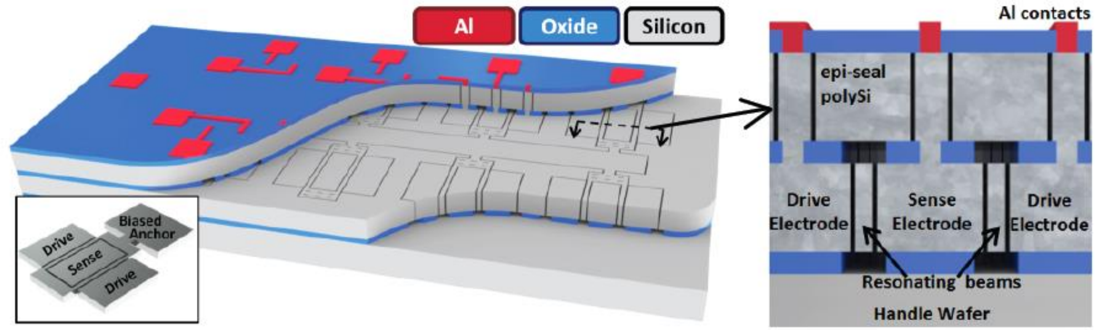
Long Term Stability

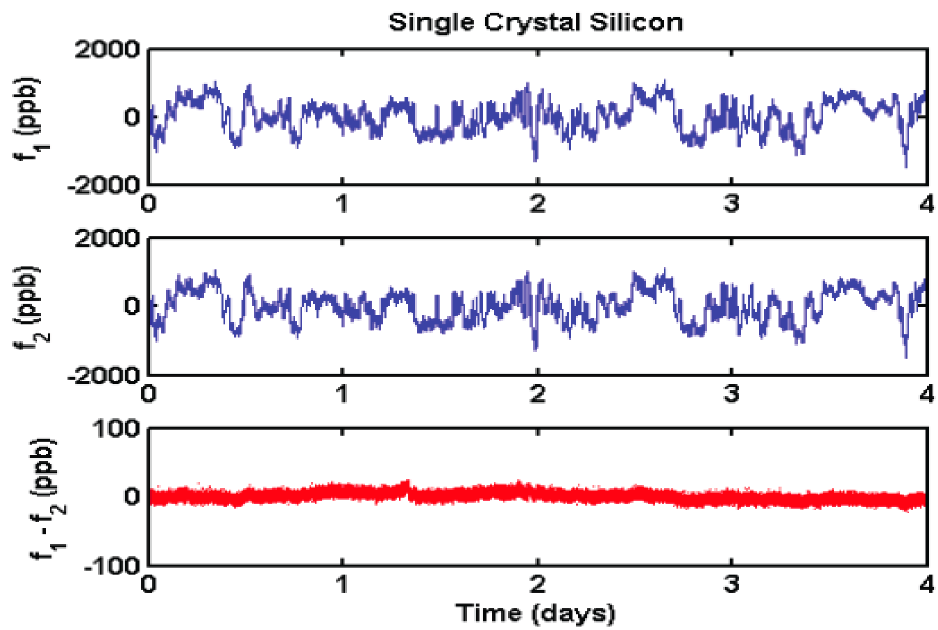


Bongsang Kim JMEMS 15,1446

Additional Benefits : Sidewall Smoothing







H2 annealing creates smooth surfaces, stable resonators

STANFORD UNIVERSITY

SiTime BOSCH

Reliability in Resonators

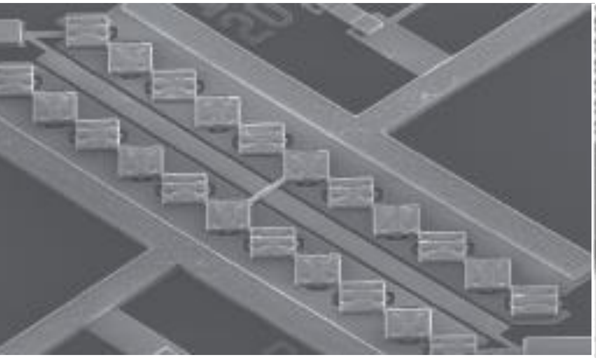
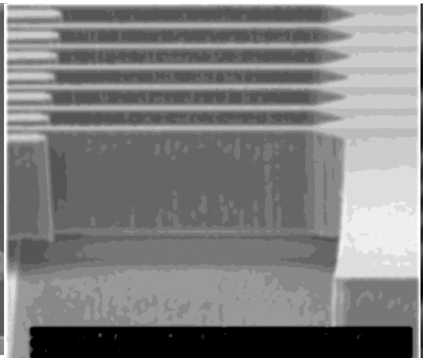
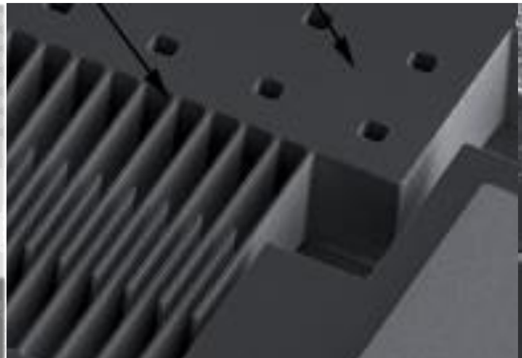
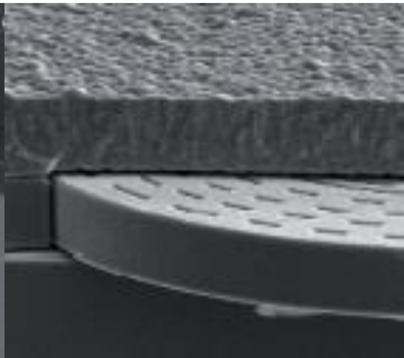
Resonators can Drift

- Adsorption/Desorption of Molecules
- Evolution/Aging of the Resonating Structure
- Failure of Hermetic Seals
- Mechanical Stress Relaxation
- Temperature Coefficient of Frequency (TCF)

All Eliminated in this Process

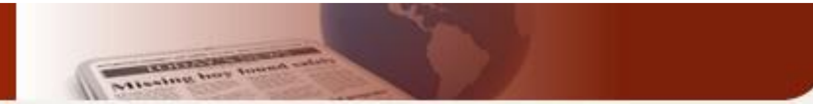
Resonators can Fail

- Contact with Surrounding Structure
- Catastrophic Failure of Package

SiTime
It's about time

The Smart Timing Choice™



The Smart Timing Choice™

CONSUMER

Low power, Small Size, Thinnest, 3-5 Week Lead Time, 100% Drop-in Replacement for Quartz

Learn more>>

Oscillators
Differential Oscillators
Low Power Oscillators
VCXO
DCXO
TCXO
Spread Spectrum
Clock Generators
Show More Products

Product Selector
Sample Requests
Application Notes
Tools and Models
Quality and Reliability
Video Library

Search by Part Numb GO

2011-10-24
SiTime Delivers Timing Industry's Highest Performance Differential Oscillators

2011-07-11
SiTime Introduces Industry's First MEMS VCTCXO with ±0.5 PPM Stability

2011-06-06
SiTime Ships 50 Million Units of its MEMS-based Oscillators, Clock Generators and Resonators

More News >>

0.5 PPM MEMS TCXO
for Telecom, Wireless, GPS

Ultra Performance Oscillator
for Telecom, Networking, Storage

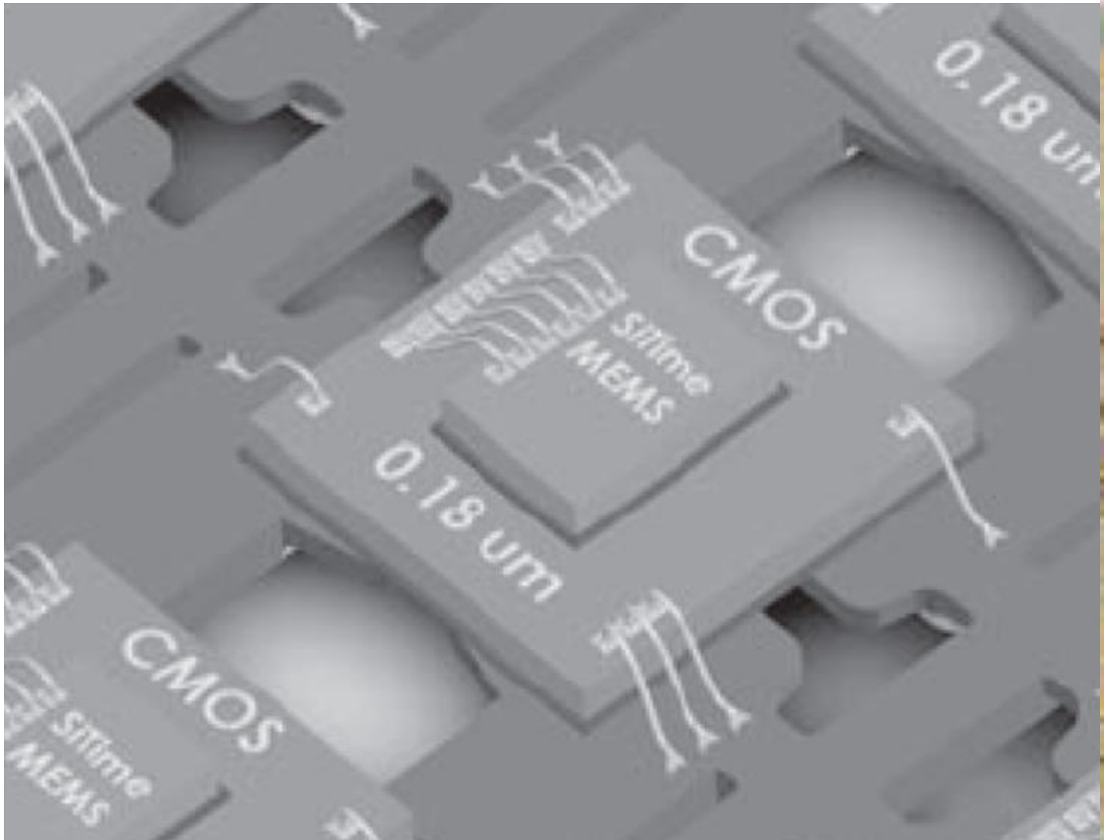
High Performance VCXO
for Telecom, Networking, Embedded

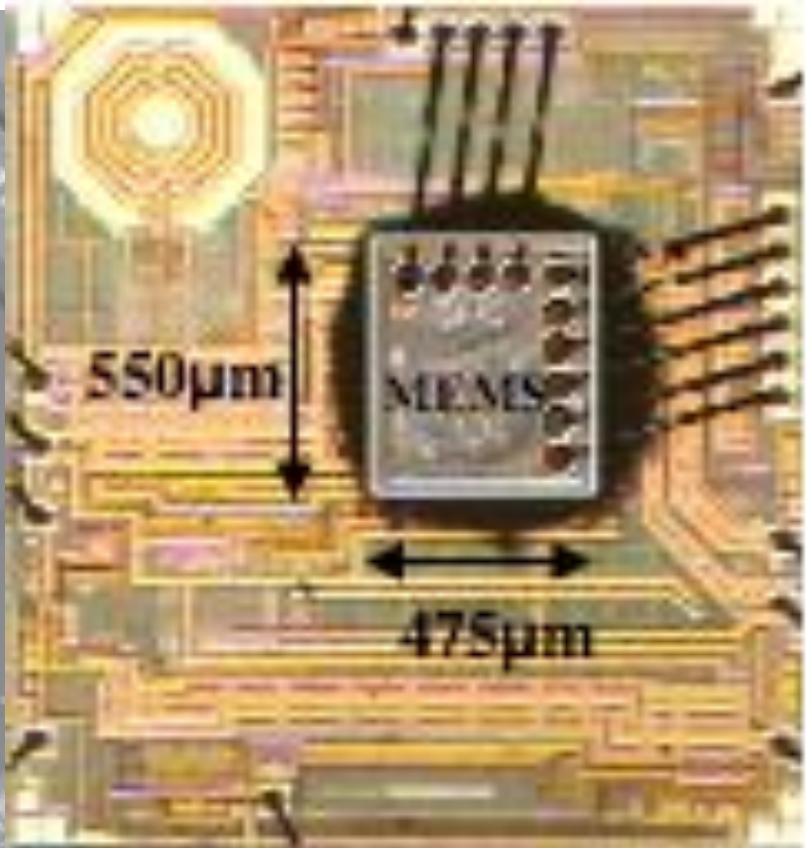
my.SiTime Login
Username
••••••
☑ Remember me
REGISTER

Product Reliability through Packaging

Ultra-Clean Chip-Scale Package

- **Eliminates all "MEMS Packaging Issues" for high reliability**
- **Allows use of Standard electronics packaging**
- **Enables minimum-volume integrated products**
- **Maintains all 2-chip opportunities Agile and Diverse Product Portfolio**





Media Contact

Piyush Sevalia
Email

SiTime Breaks into High-Precision OCXO Timing with Stratum 3 Solutions

World's Smallest ±100 PPB Oscillators Consume One-Tenth the Power of OCXOs

SUNNYVALE, Calif. – November 15, 2011 – SiTime Corporation, an analog semiconductor company, today introduced the SiT530x family of Stratum 3 compliant silicon MEMS timing solutions that replace OCXOs and TCXOs. The SiT5301 and SiT5302 are targeted at telecom and networking infrastructure such as SONET and Synchronous Ethernet based core and edge routers, wireless base stations, IP timing and smart grid applications. The SiT530x family uniquely combines Stratum 3 stability with small size, low voltage operation and programmable features that allows customers to quickly and easily customize and differentiate their products.

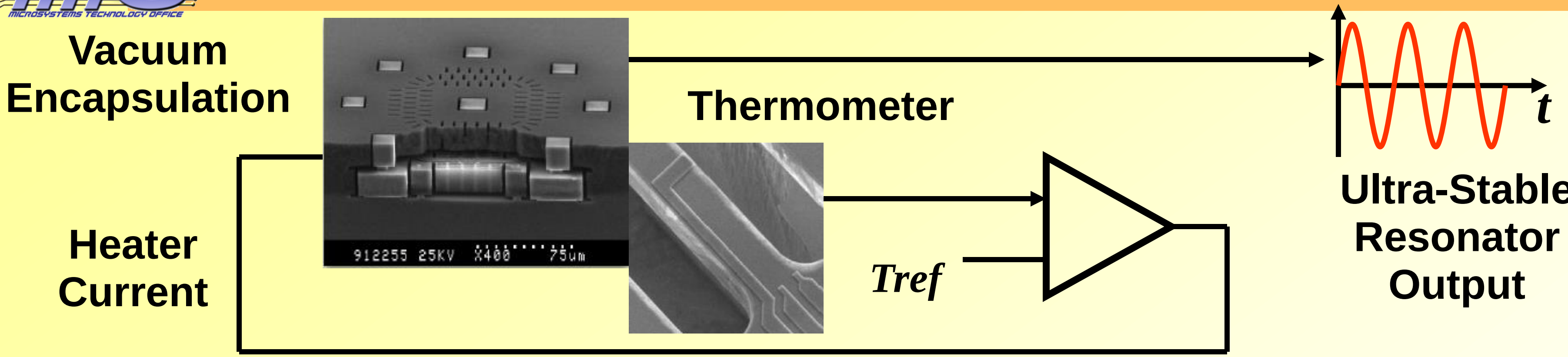
"SiTime's revolutionary technology integrates silicon MEMS and analog ICs to deliver innovative solutions. The quartz industry took decades to deliver this level of precision; SiTime, in 5 years, has broken through the same performance level. With our semiconductor expertise we have added unique features that offer additional value to the customer," said Rajesh Vashist, CEO of SiTime. "With game-changing products like the Stratum 3 clocks, and our recently announced differential oscillators and VCXOs, SiTime is accelerating the adoption of silicon MEMS timing products. SiTime is now addressing an oscillator market of $1 billion. Our remarkable combination of performance, lower cost and ease-of-use has successfully converted over 500 customers away from legacy quartz products."

SiTime Status

- >150M Oscillators shipped
- High-Yield MEMS + Advanced Mixed Signal CMOS = Diverse and adaptive product portfolio.
- 50,000g shock survival
- No Failed MEMS in any shipped products
- Entering TCXO, OCXO, Low-Power Real-Time Clock and Ultra low-cost baseline oscillator markets.

- MEMS Will replace Quartz
- MEMS is *more reliable* than Quartz

Encapsulated Resonator Milestones



Micromechanical Resonator Reference Oscillator Metrics	State-of-the-Art	18 mo. Milestone	36 mo. Milestone	Program Goal (4.5 Yrs.)
Enclosure Vacuum (Vent Rate) [mTorr/yr]	n/a	1000@30C	10@125C	0.1@125C
Resonator Quality Factor @100 MHz	100	n/a	15,000	20,000
Size for Encapsulated, Ovenized Device	10cm^3	n/a	0.25 cm^3	0.005 cm^3
Fractional Freq. Change (-55 to 125 degC)	150 ppm	150 ppm	1.5 ppm	0.015 ppm
Phase Noise @ 1kHz on Vibrating Platform	n/a	-95 dBc/Hz	-120 dbc/Hz	-150 dBc/Hz
Fractional Freq. Change after 20,000 g	n/a	n/a	100 ppm	5 ppm
Power Consumption	2.5W	200 mW	20 mW	5 mW

Resonators

Opportunity :

- High Q, tunable frequency, good range, nice properties
- Low Cost
- Standard processes for all manufacturing and packaging
- Potential for integration with IC for “Single-Chip systems”
- Success in Commercialization

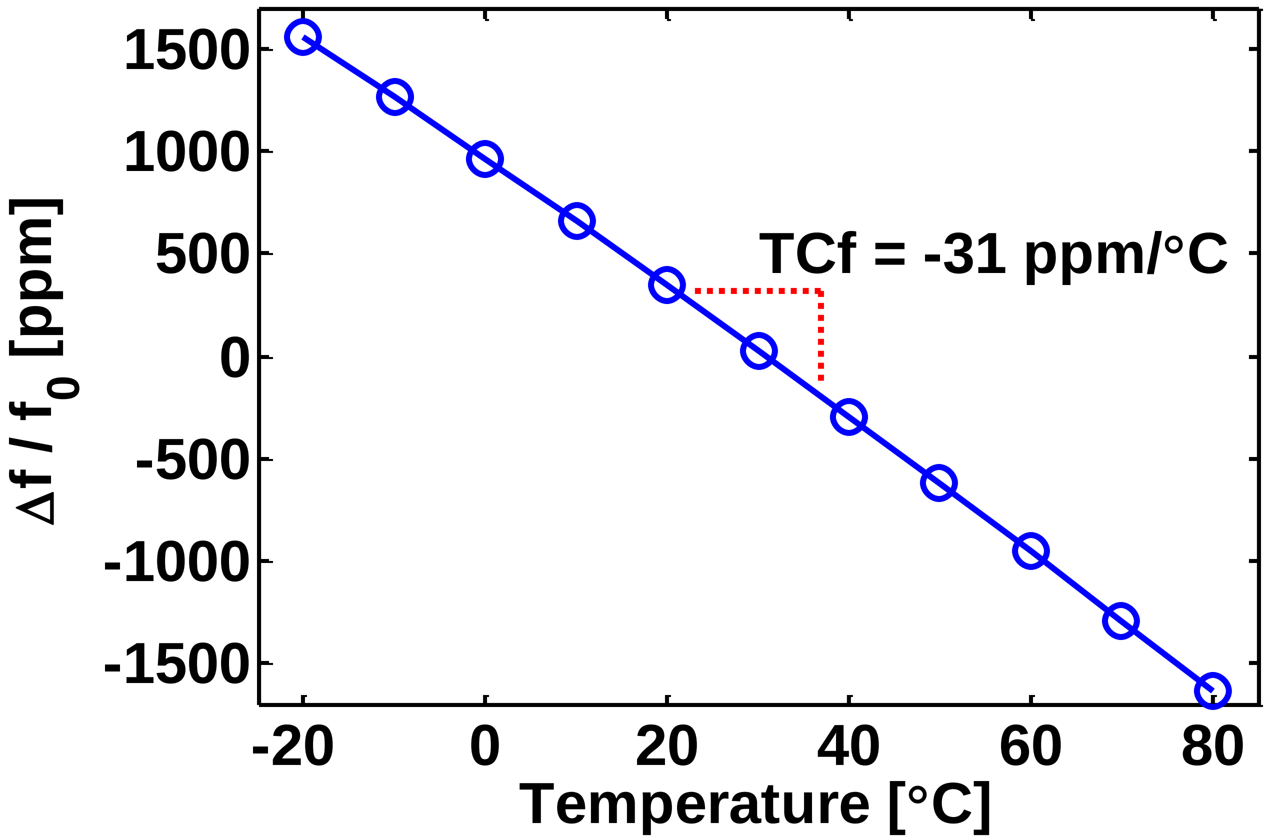
Barriers :

- MEMS resonators MUST be packaged
- Random Frequency Drift, Aging
- Silicon has a high temperature coefficient of modulus - frequency drift more than 10x worse than quartz resonators

Ultra-Stable (<1ppm) Oscillators require additional effort

STANFORD
UNIVERSITY

Temperature Sensitivity of Silicon Resonators

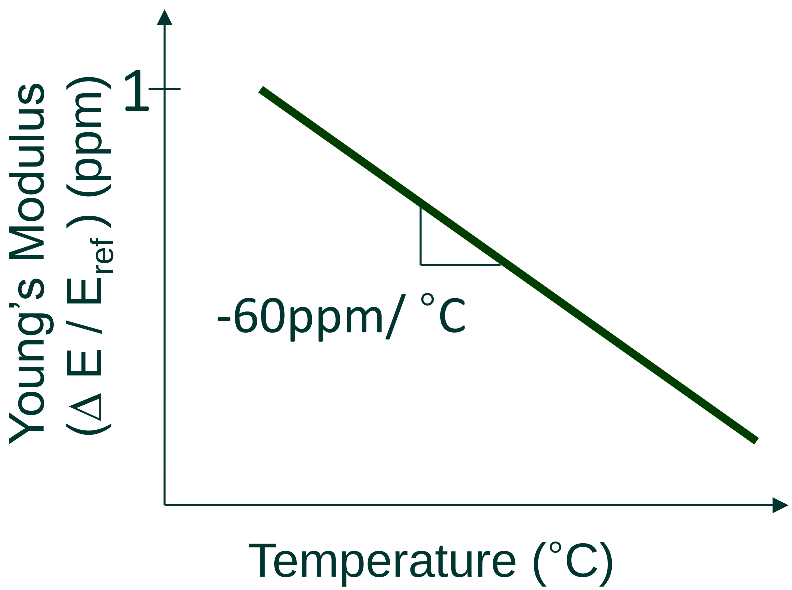


Dominated by temperature dependence of Elastic Modulus

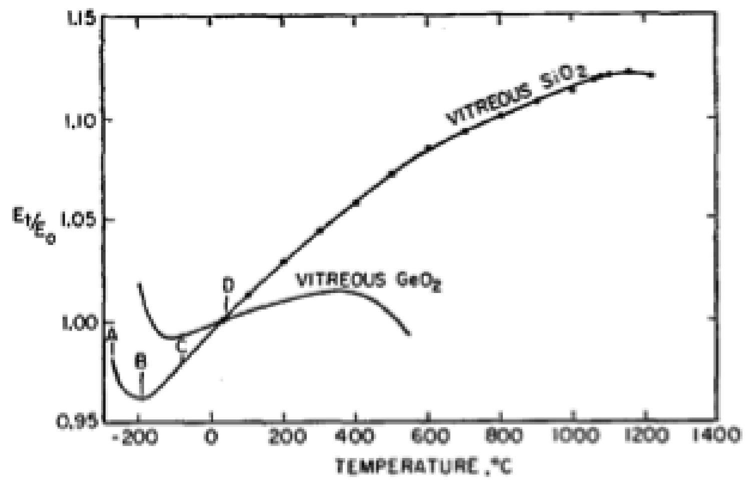
Small contribution from Thermal Expansion

Temperature Stability Strategy

Silicon Young's Modulus



Elastic Modulus of SiO_2 vs. Temperature



Spinner, S. and Cleek, G. W. (1960). "Temperature Dependence of Young's Modulus of Vitreous Germania and Silica." Journal of Applied Physics, 31(8): 1407-1410.

- **Silicon becomes softer with increase in temperature**
- **Silicon dioxide (SiO_2) becomes stiffer as temperature increases**
- **Combination of Si and SiO_2 will compensate resonant frequency change due to temperature change**
- **SiO2 can be added to our fabrication sequence.**

Renata Melamud, Bongsang Kim, Matt Hopcroft, …

Resonator History

XP-002462194

IBM Technical Disclosure Bulletin Vol. 14 No. 4 September 1971

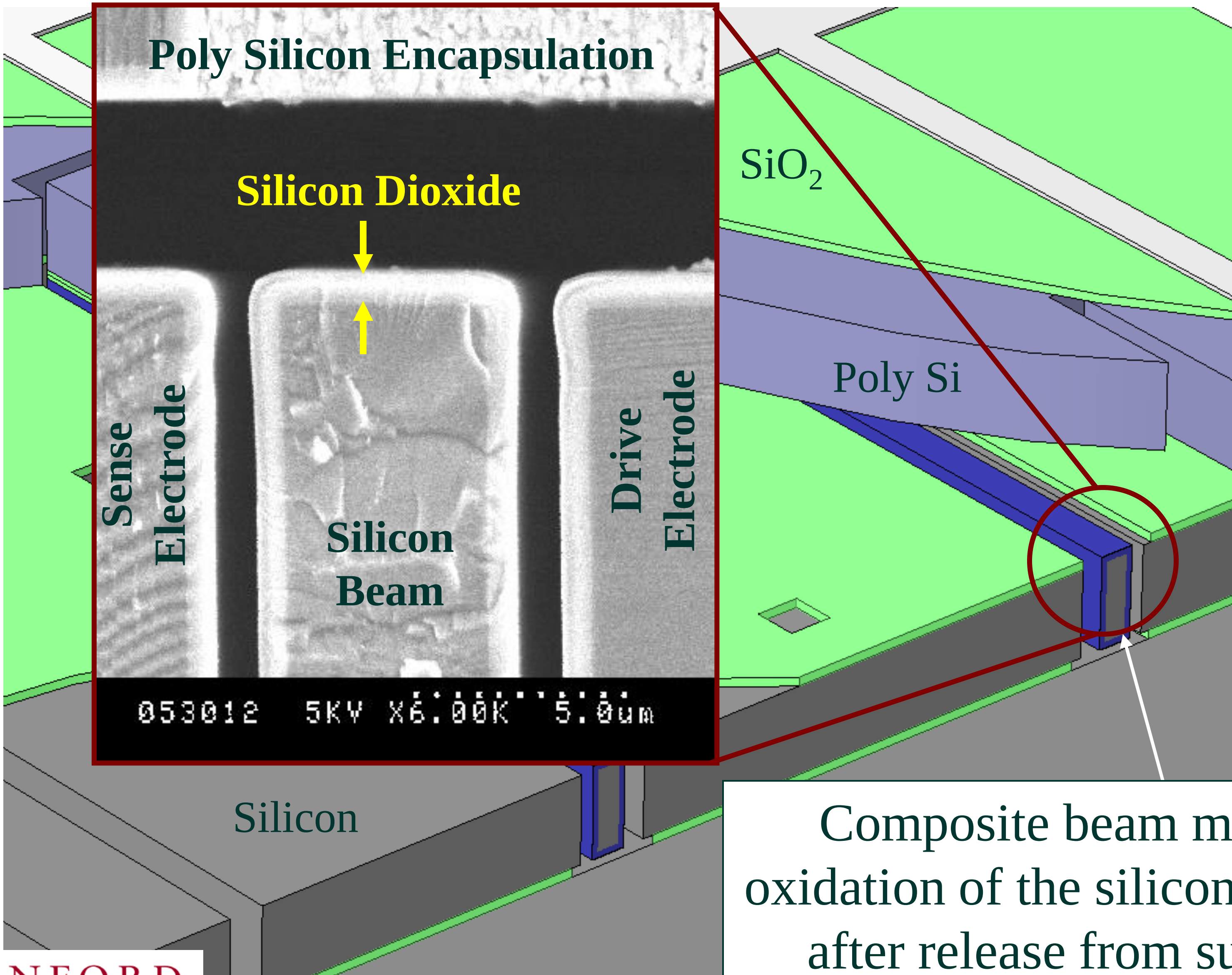
TEMPERATURE COMPENSATION FOR CONSTANT-FREQUENCY ELECTROMECHANICAL OSCILLATORS

B. S. Berry and W. C. Pritchet

Electronically maintained mechanical oscillators, such as a reed or tuning fork, are useful as generators of reference AC frequency signals of high stability. The overall frequency stability of such a device depends on a number of factors, of which the most important is usually the effect of temperature on the elastic modulus of the material.

For the silicon reed electromechanical oscillator, the sign of β is negative. It is known that β is positive for certain amorphous oxides and, in particular, amorphous (fused) silica (SiO_2) has a substantial positive value of β over a wide-temperature range (- 190°C to +1200°C). Therefore, an overcoat of amorphous SiO_2 may be used to increase the temperature stability of the silicon reed device.

Stiffness Compensation to Reduce TCF

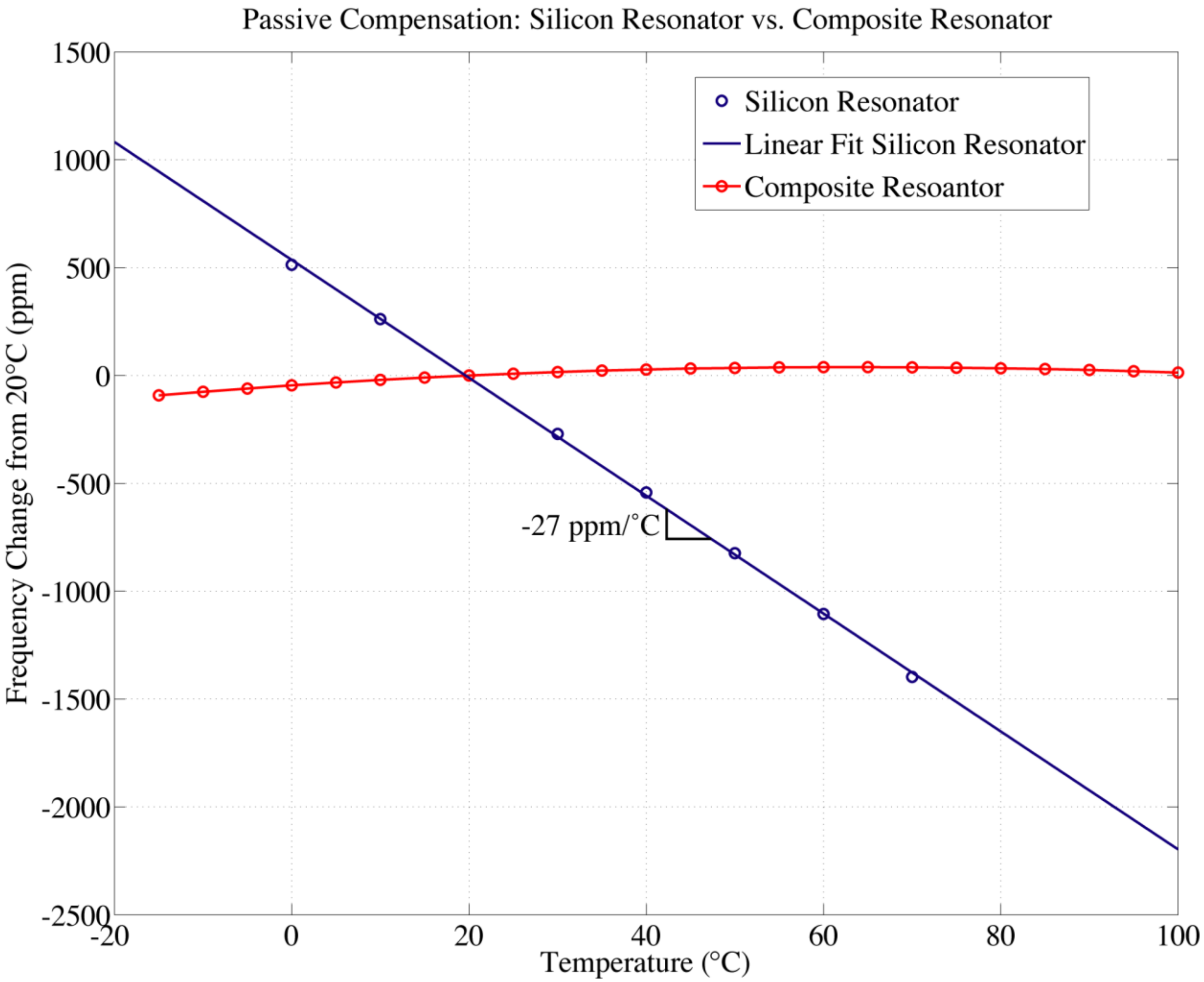


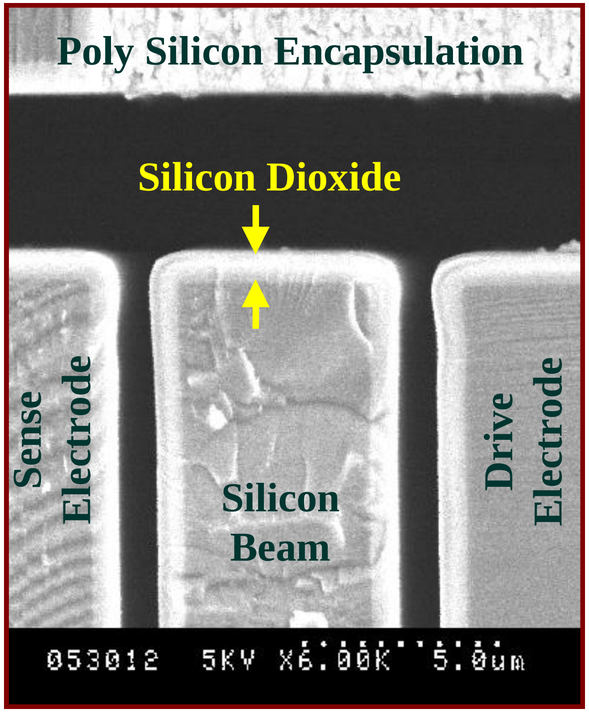
Composite beam made by oxidation of the silicon resonator after release from substrate

STANFORD UNIVERSITY

Renata Melamud, Bongsang Kim, Matt Hopcroft, …

Stiffness Compensation to Reduce TCF





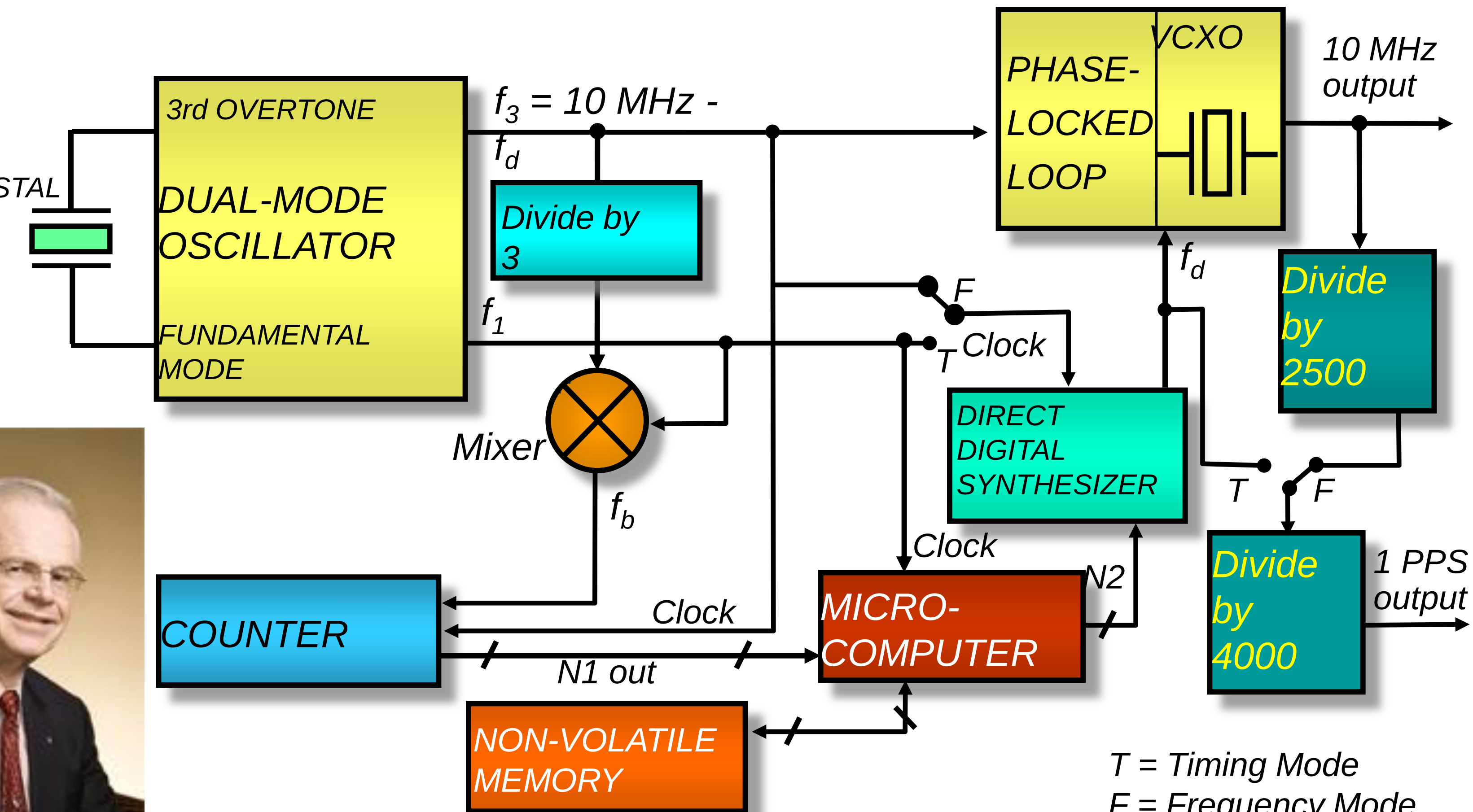
Should provide 20x reduction in frequency error of resonators without any other improvements

STANFORD UNIVERSITY

Renata Melamud, Bongsang Kim, Matt Hopcroft, …

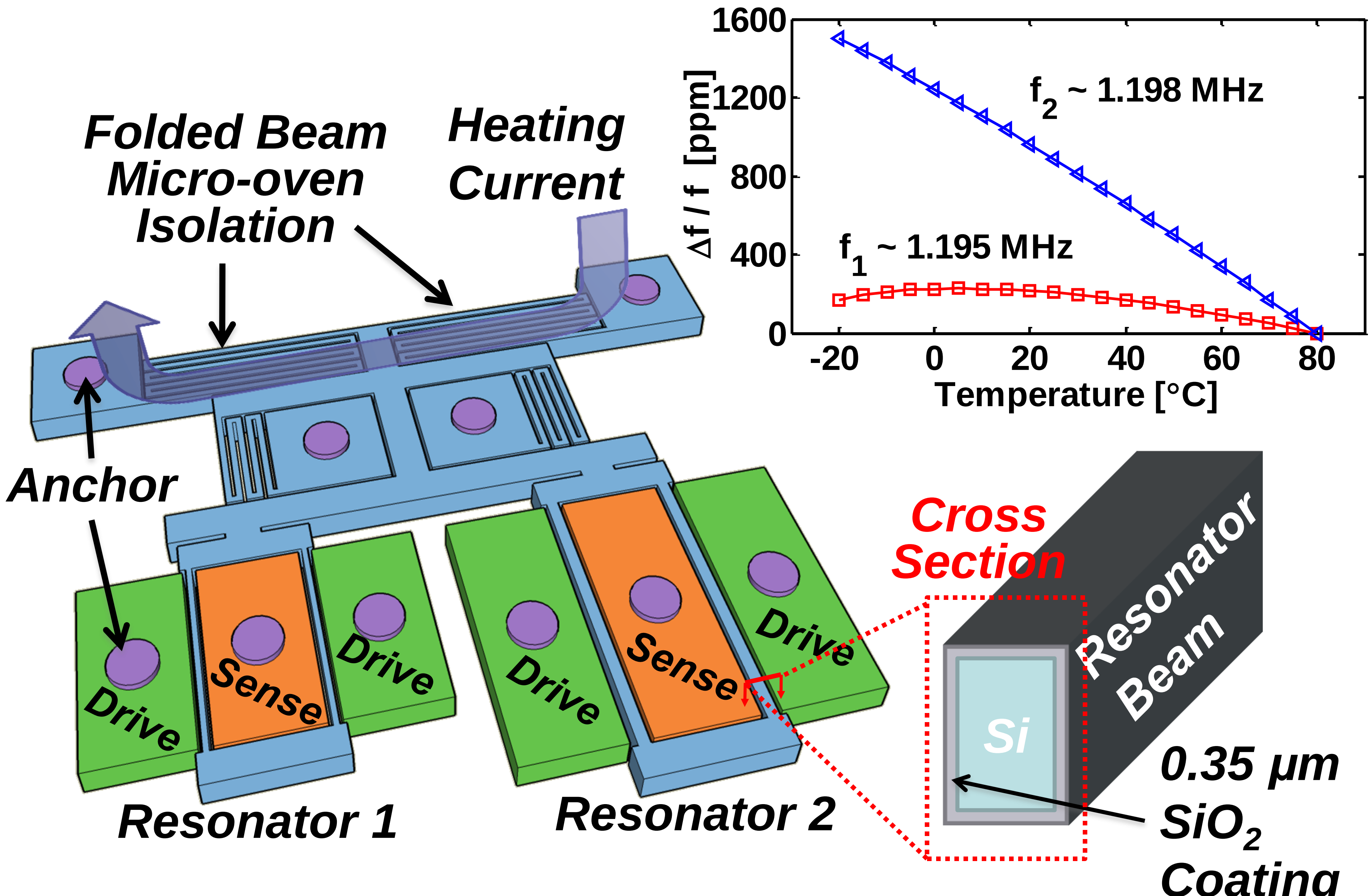
MCXO Frequency Summing Method

Block Diagram



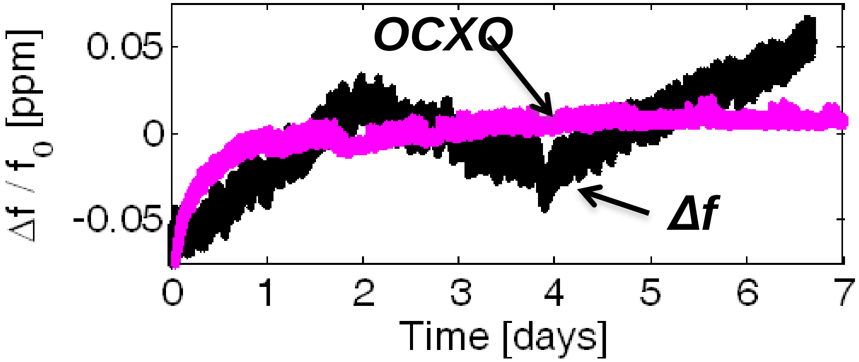
A. Benjaminson and S. Stallings, "A Microcomputer-Compensated Crystal Oscillator Using Dual-Mode Resonator," Proc. 43rd Annual Symposium on Frequency Control, pp. 20-26, 1989, IEEE Catalog No. 89CH2690-6.

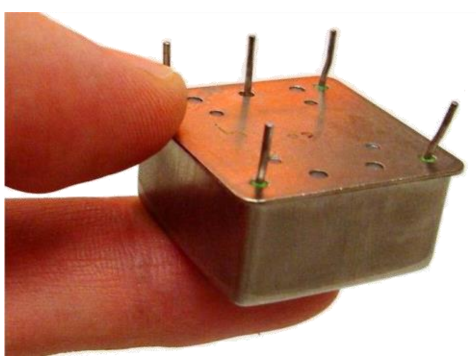
Dual Composite Resonators in Micro-Oven



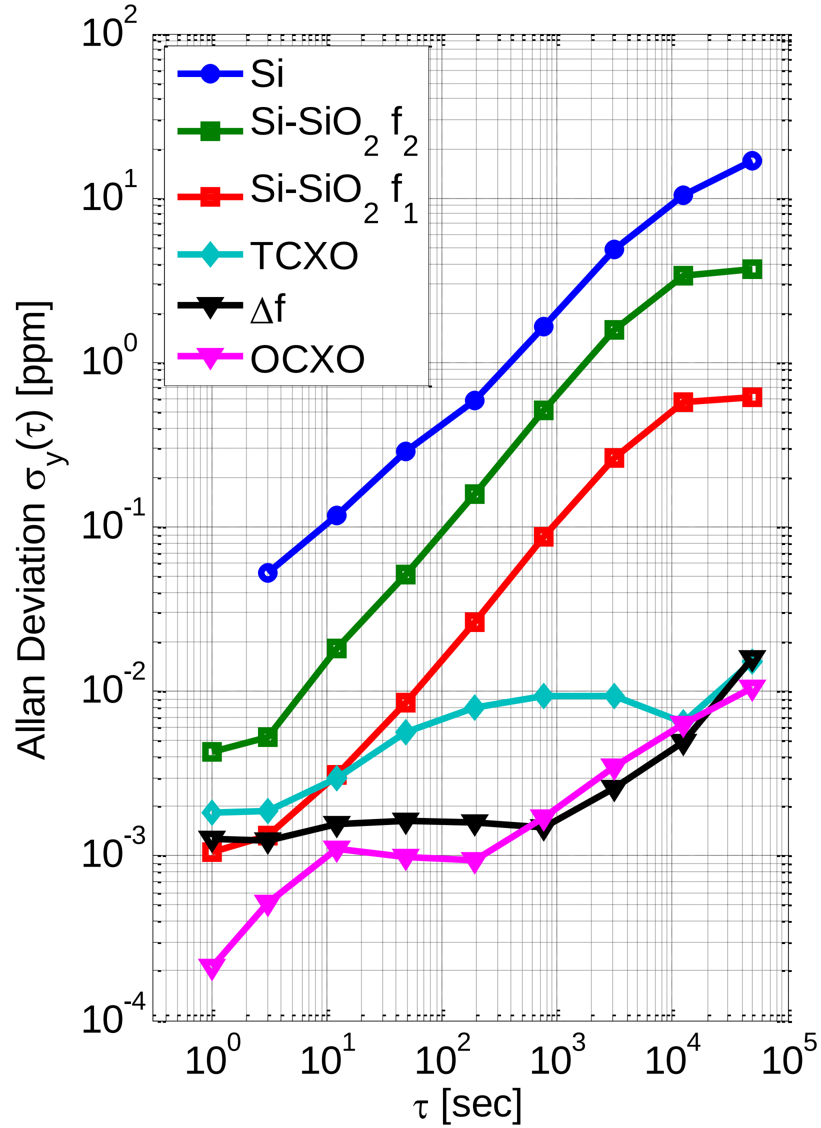
Renata Melamud, Matt Hopcroft, Bongsang Kim, Chandra Jha, Jim Salvia

Oscillator Stability Comparison





Quartz OCXO
Vectron (Corning) C4550 100 MHz

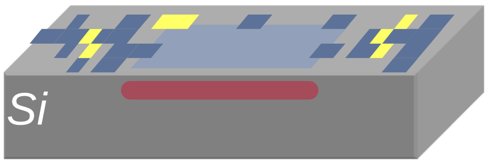


STANFORD
UNIVERSITY

Pressure, Accelerometer, Gyroscopes

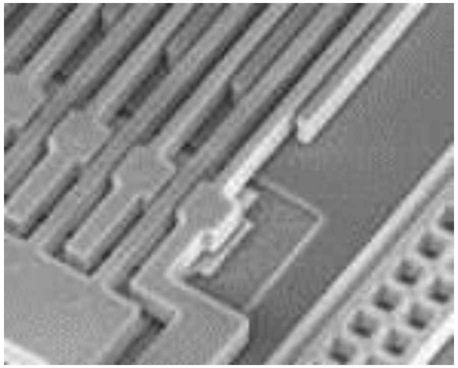
3 sets of requirements, leading to 3 distinct fab processes and 3 distinct packages

Pressure



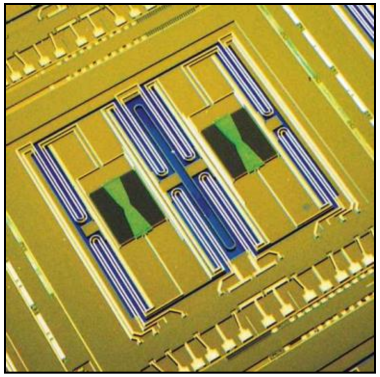
- Sealed Reference Chamber
- Surface exposed to ambient
- Piezoresistive Transduction

Accelerometer



- Sealed Chamber
- Packaged with pressure for critical damping
- Small displacements
- Capacitive Transduction

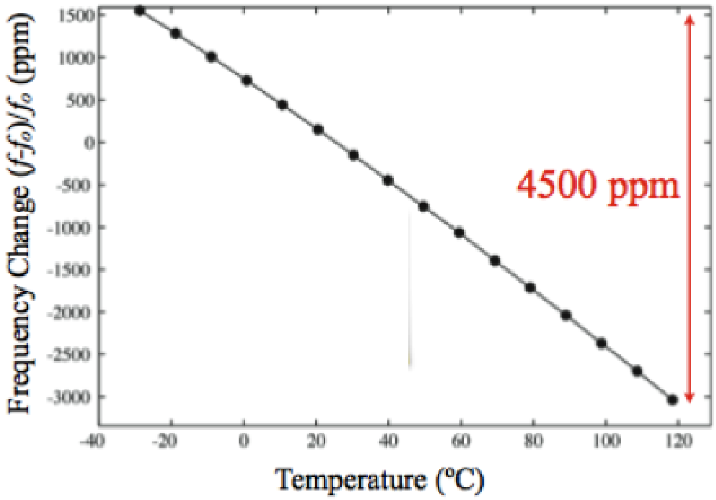
Gyroscope



- Sealed Chamber
- Vacuum for High Q
- Large displacements
- Capacitive Transduction

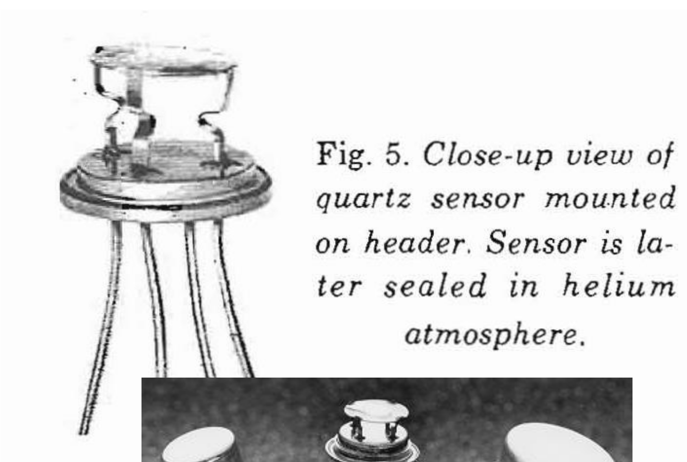
Multi-Sensor Product would require many distinct MEMS chips in single product package – impossible to get to mm-scale

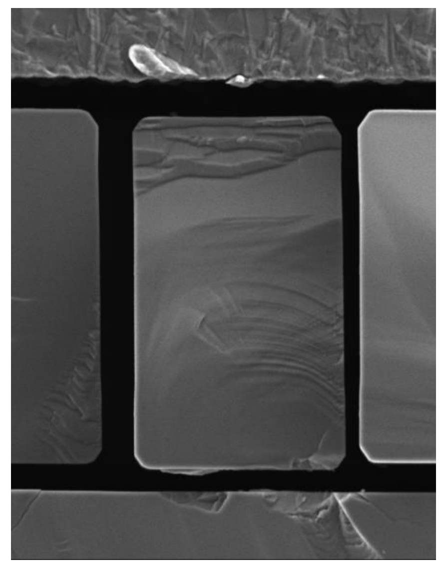
MEMS Resonant Thermometer?

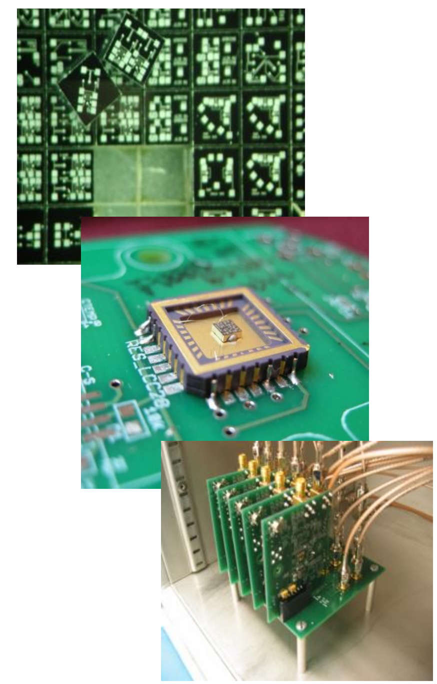


1970 : HP Quartz Resonant Thermometer

2012 : Stanford Si Resonant Thermometer?



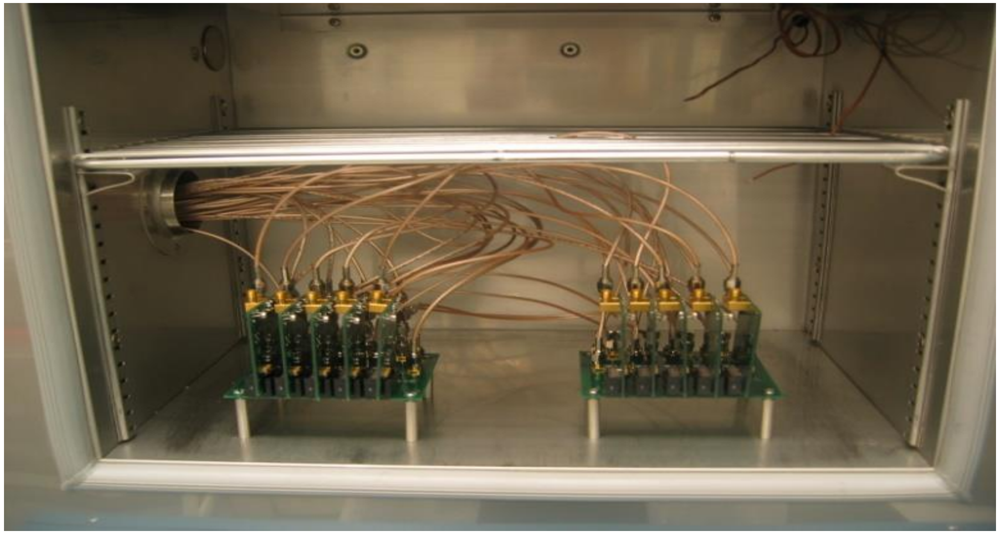


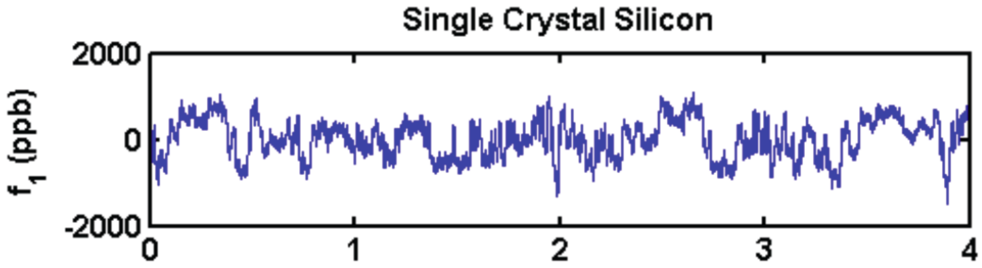


STANFORD UNIVERSITY

Eldwin Ng, Shasha Wang

MEMS Resonant Thermometer?





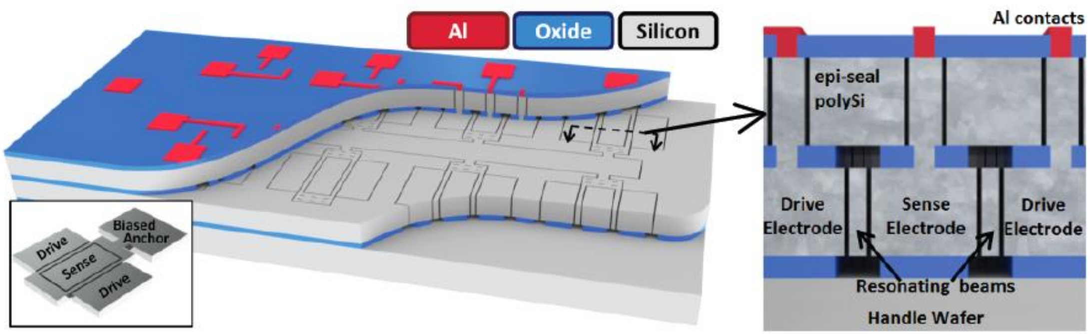
Challenge :

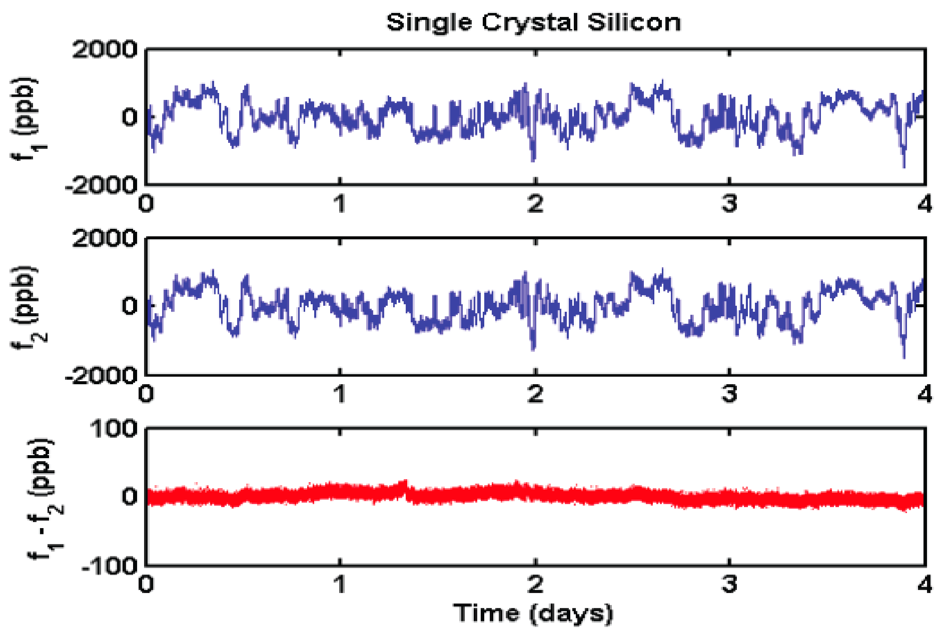
Frequency Variations in Resonators can be Dominated by Environmental Temperature Variations, instead of Fundamental Noise in the Resonator.

How to test your most accurate thermometer?

Eldwin Ng, Shasha Wang

Encapsulated Resonant Thermometer?





Solution :

Operate Multiple Resonators in Same Die.

Result – True Long-term Frequency Variations are <10 ppb, leading to temperature resolution of better than 0.0005C

This thermometer can be co-fabricated with clocks and inertial sensors for accurate temperature control or compensation.

Eldwin Ng, Shasha Wang

Encapsulated Pressure Sensor + Thermometer

A NOVEL, HIGH-RESOLUTION RESONANT THERMOMETER USED FOR TEMPERATURE COMPENSATION OF A COFABRICATED PRESSURE SENSOR

Chia-Fang Chiang[1], Andrew B. Graham[2], Eldwin J. Ng[1], Chae Hyuck Ahn[1], Gary J. O'Brien[2], and Thomas W. Kenny[1]
[1]Stanford University, Stanford, CA, USA and [2]Robert Bosch RTC, Palo Alto, CA, USA

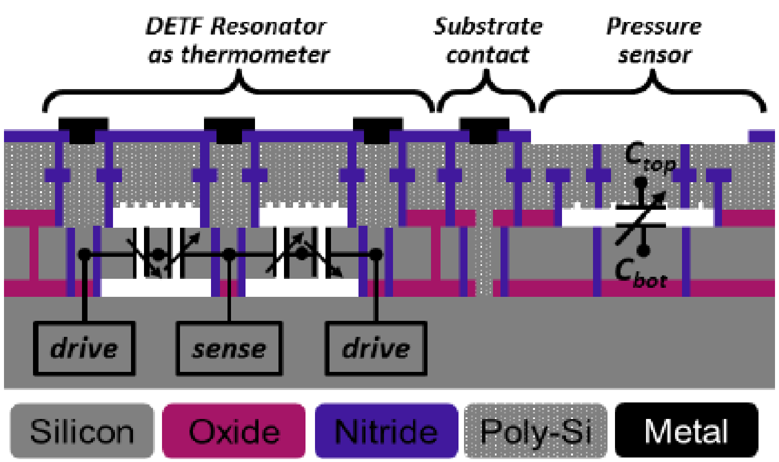


Figure 1: A cross-sectional view of the cofabricated DETF resonant thermometer and capacitive pressure sensor.

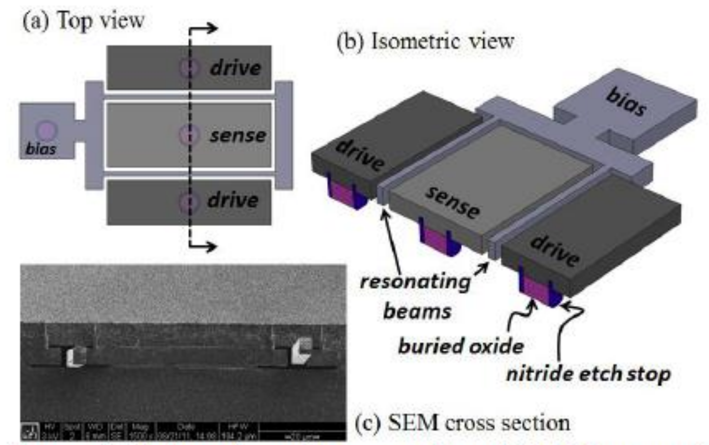


Figure 2: Schematic and cross-sectional SEM images of a DETF resonant thermometer.

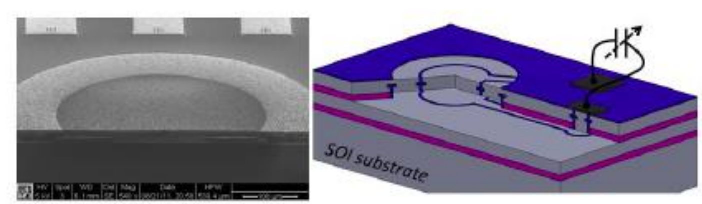
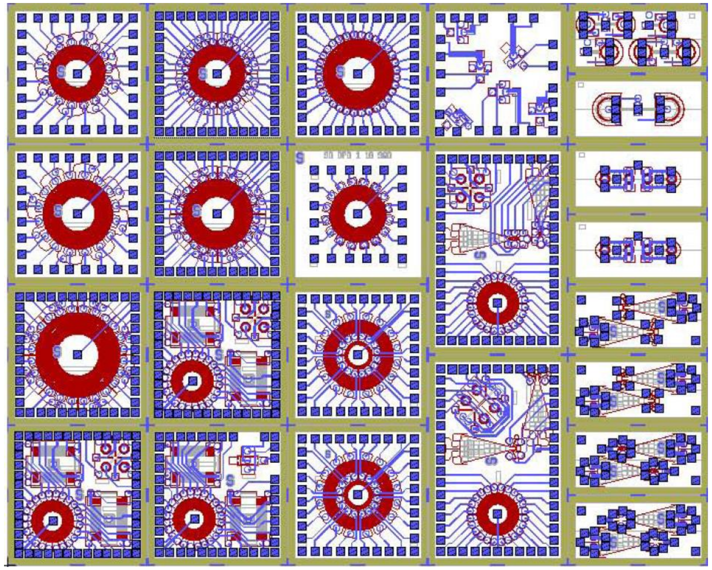
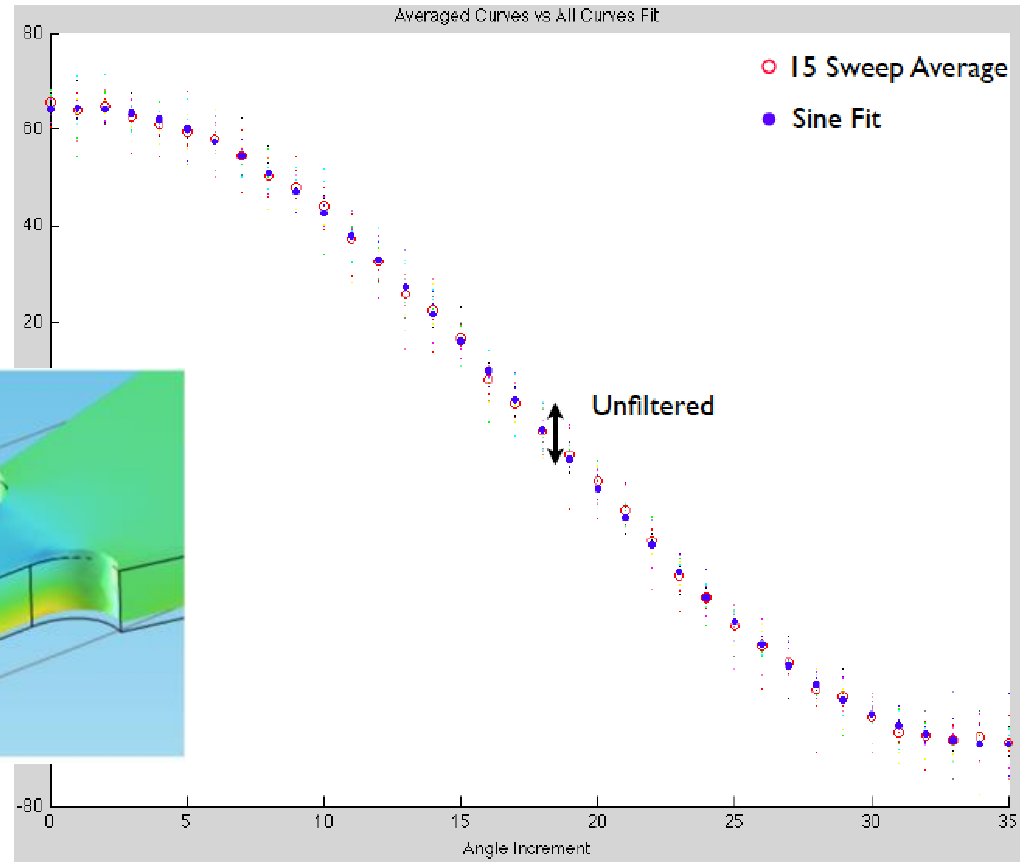


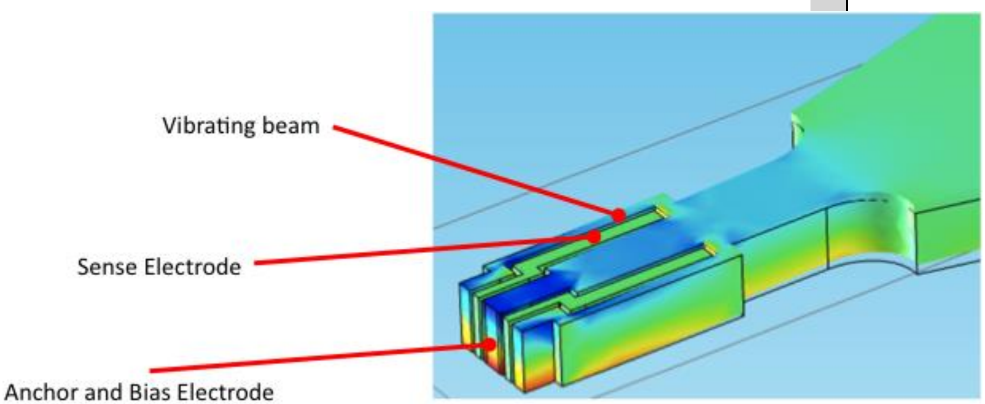
Figure 3: Structure of the capacitive pressure sensor.

Encapsulated Resonant Accelerometer?



Since we were making resonant thermometers, we also attempted a resonant accelerometer



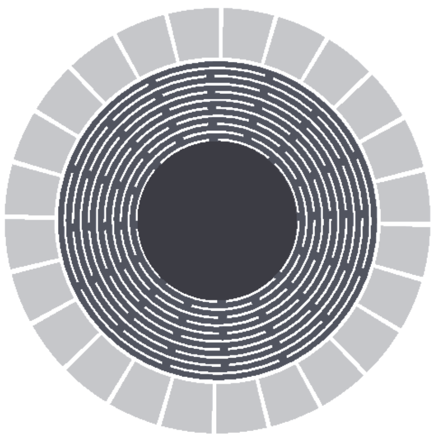


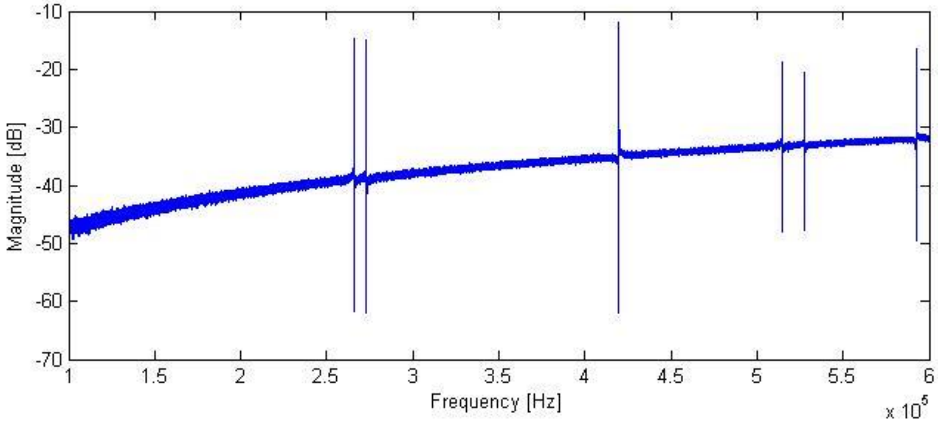
STANFORD
UNIVERSITY

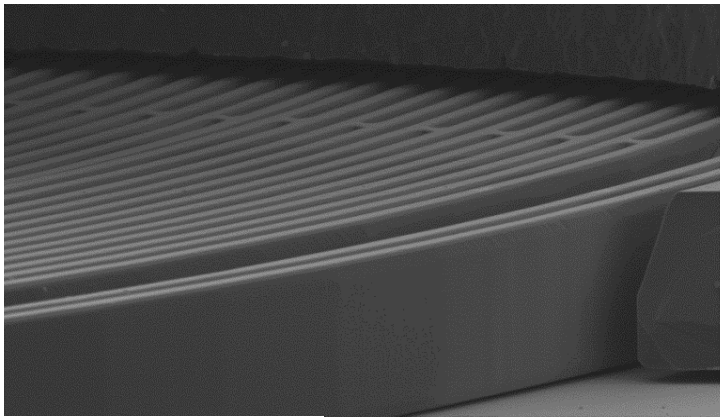
Eldwin Ng, Shasha Wang, David Christensen

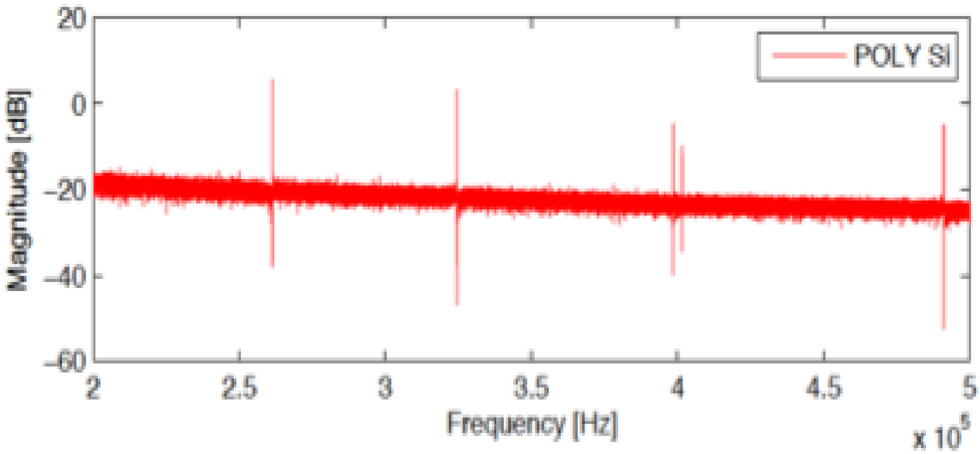
Encapsulated Resonant Gyroscope

Since we were making resonant theromometers and accelerometers, we also attempted a prototype wine-glass gyro









STANFORD UNIVERSITY

Eldwin Ng, Shasha Wang, Chae-Hyuck Ahn

Encapsulated MEMS

Developing the MEMS and the Package together has some benefits

- Improved Materials Performance
- Opportunities to improve the device one characteristic at a time
- Ovenization and materials compensation examples shown
- Short path to commercialization?
- Interesting platform for MEMS materials and device research?
- Pathway to many other MEMS devices in a common process?

SiTime It's about time

BOSCH

STANFORD UNIVERSITY