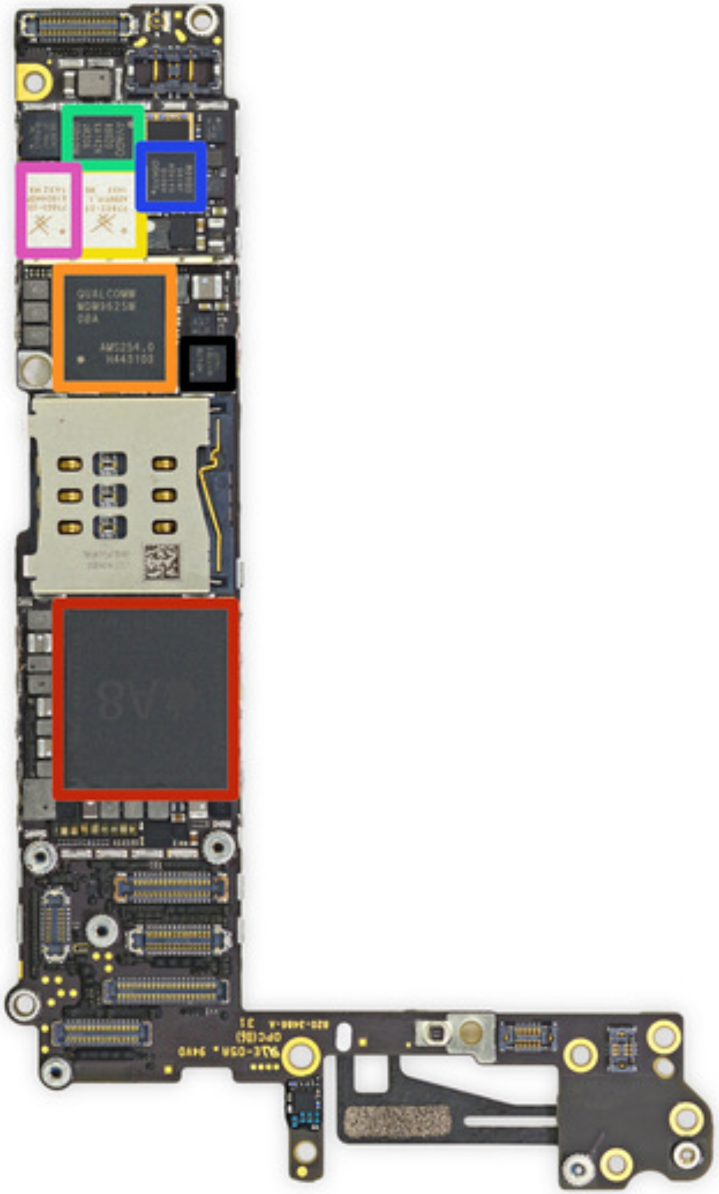
The LONG Path from MEMS Resonators to Timing Products

Eldwin Ng, Yushi Yang, Vu Hong, Chae Ahn, David Heinz, Ian Flader, Yunhan Chen, Camille Everhart, Bongsang Kim, Renata Melamud, Rob Candler, Matt Hopcroft, Jim Salvia, Shingo Yoneoka, Andrew Graham, Matt Messana, HyungKyu Lee, Shasha Wang, Gaurav Bahl, Violet Qu, and Thomas Kenny
Department of Mechanical Engineering, Stanford University, Stanford, CA

Aaron Partridge, Markus Lutz SiTime Corp
Gary O' Brien, Gary Yama Bosch RTC

MEMS – a truly HOT topic these days



Apple iPhone 6

6-axis Gyro/Accel (Invensense)
3-axis Accelerometer (Bosch)
3-axis Magnetometer (AKM)
3 microphones (Knowles)
Pressure Sensor (Bosch)

A trillion MEMS Sensors coming soon!

The First MEMS Device – 50 years ago!

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

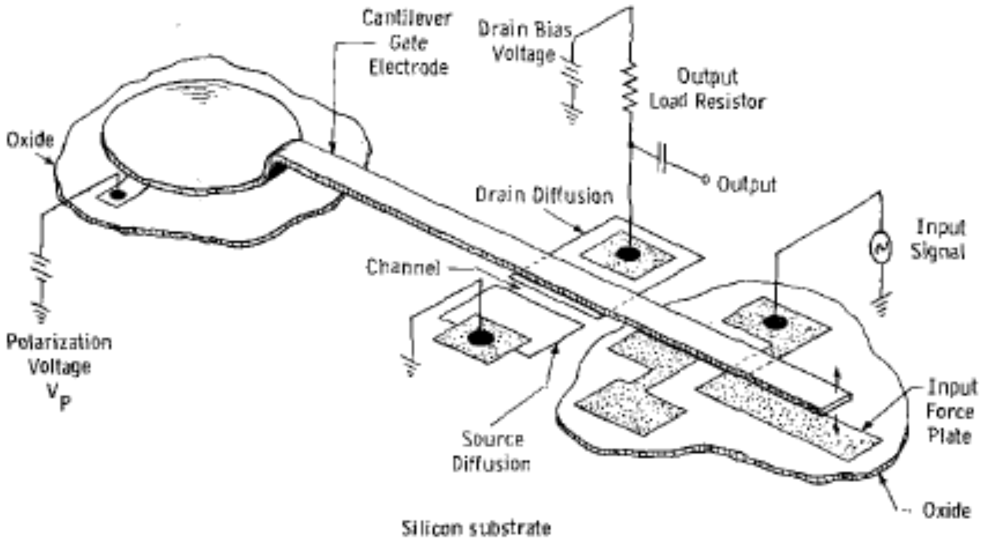
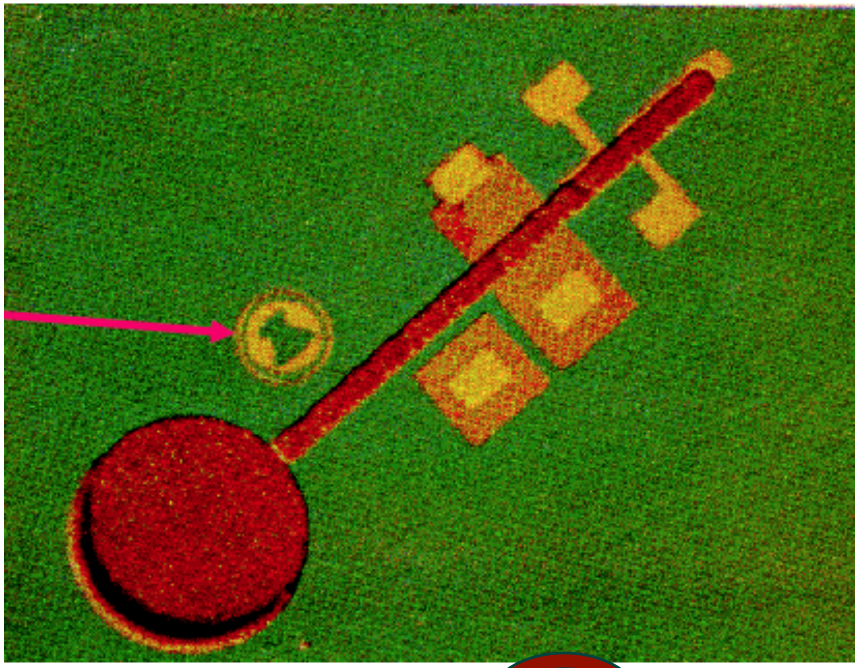
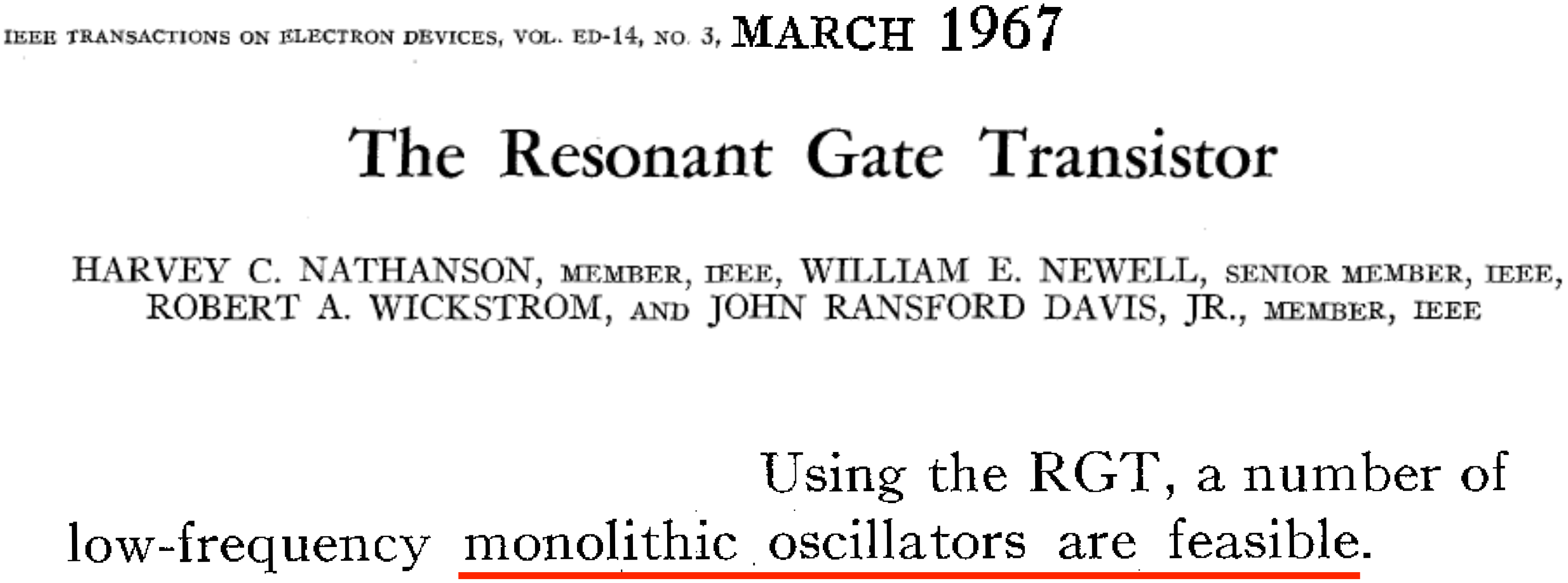


Fig. 1. Geometry and circuit connections of an RGT with a C-F resonant beam.



Electronics, Sept. 20, 1965 (cover)

The Long Path from MEMS Resonators to Timing Products Begins here



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

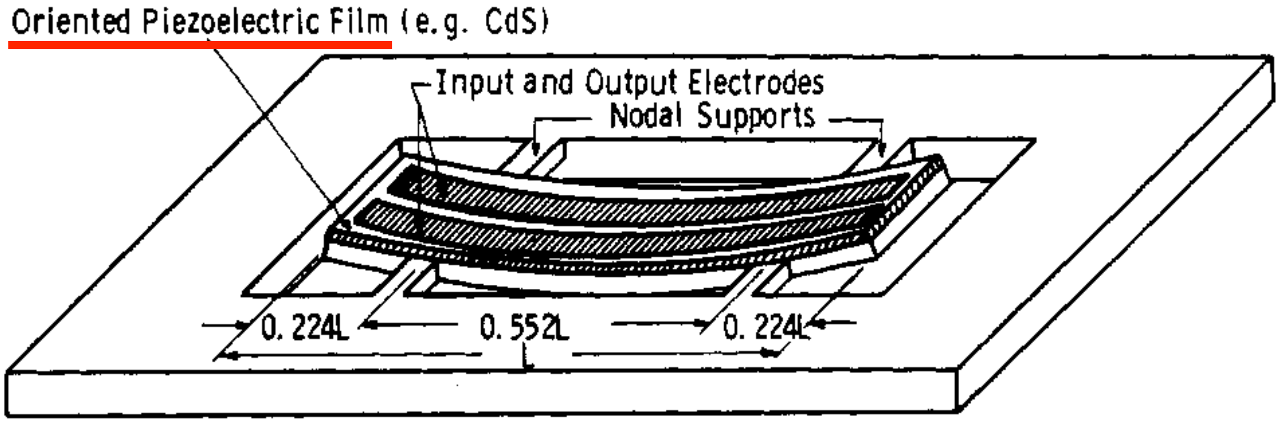
Using the RGT, a number of low-frequency monolithic oscillators are feasible.

Very Fast Early Progress!

SEPTEMBER 1969

The Tunistor: A Mechanical Resonator for Microcircuits

WILLIAM E. NEWELL, SENIOR MEMBER, IEEE, AND ROBERT A. WICKSTROM



Only a few years ago, the idea that mechanical resonators could be made to be compatible with monolithic and hybrid microcircuits was quite revolutionary. However, the feasibility of such devices has now been demonstrated over a very wide frequency range.

Feasibility Proven in 1971.

When did MEMS Timing Products Appear?

What Took SO LONG??

Simple Answer : MEMS Wasn’t Ready in 1971

Simple Answer : MEMS Wasn’t Ready in 1971

MEMS Resonators need a Vacuum Package

Low pressure required for high Q.

Package must be Compact and Hermetic.

MEMS Resonators Suffered from Aging

Many observations of drift, “burn-in”, fatigue.

MEMS Reliability Research just beginning

MEMS Resonators have too much F(Temperature)

30 ppm/C is too large for timing applications.

Compensation not practical.

MEMS Wasn’t Ready in 1971

We Needed Help!

- Partners
- $$
- Motivation

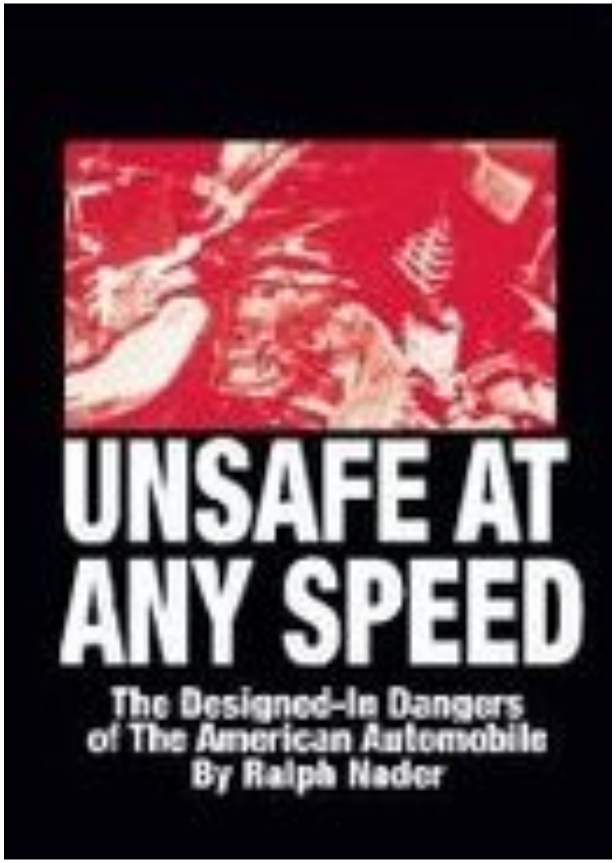
We needed to build a Technology!

The History of Vehicle Highway Safety

1965: Nader' s "Unsafe at Any Speed, led to passage of National Highway Traffic Safety Act. Soon : A requirement for seat belts as standard equip.

1971: Ford, GM, Chrysler begin providing airbags as optional equipment.

1980s : Chrysler begins marketing Safety as a Significant Feature.
MEMS is identified as a technology that can improve the Safety of Automobiles.



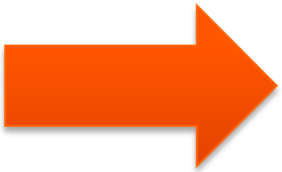
The Automotive Industry Needs Help

MEMS to the Rescue!!!

Cars and MEMS – A Symbiotic Relationship

Cars Need MEMS

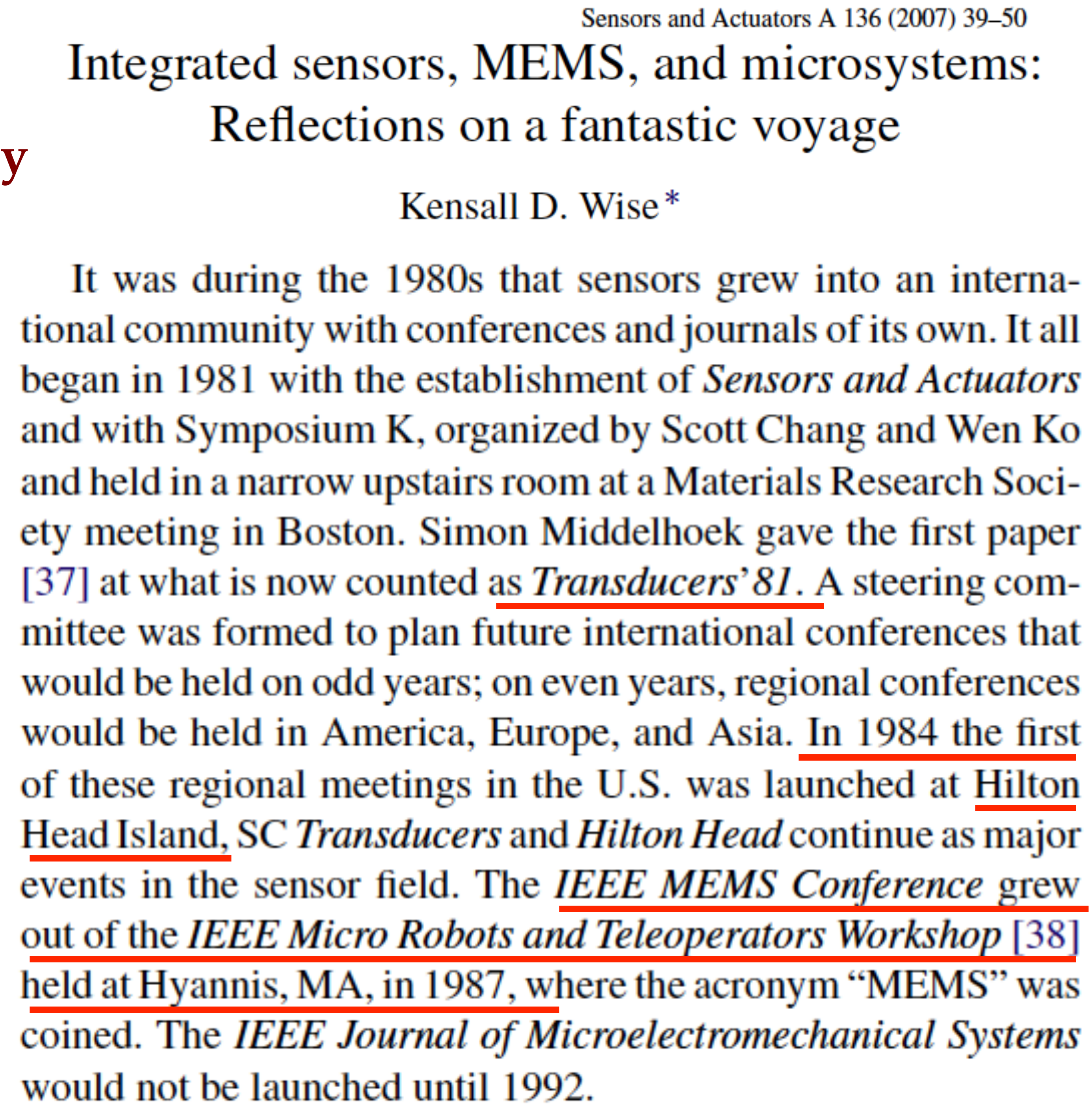
- **Safety**
- **Pollution**
- **Comfort**
- **Entertainment**



Auto Industry Needs led to Funding for Technology Development of Sensors for Automotive Industry

Indirectly, this led to MEMS

A Community is Born!



Sensors and Actuators A 136 (2007) 39–50

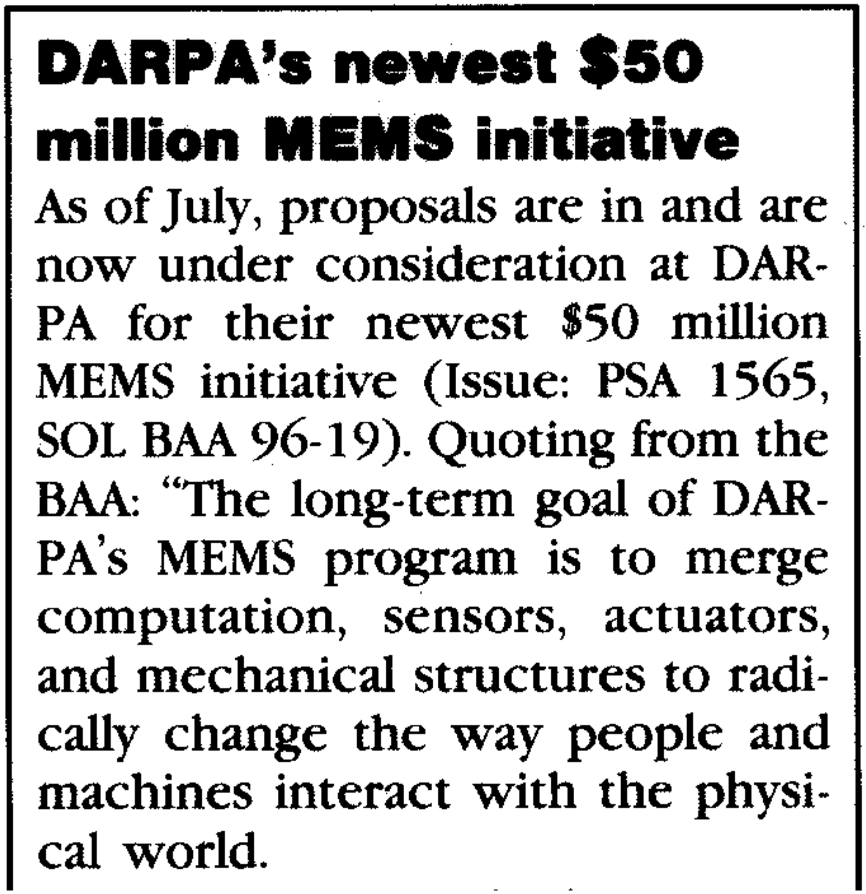
Integrated sensors, MEMS, and microsystems: Reflections on a fantastic voyage

Kensall D. Wise*

It was during the 1980s that sensors grew into an international community with conferences and journals of its own. It all began in 1981 with the establishment of *Sensors and Actuators* and with Symposium K, organized by Scott Chang and Wen Ko and held in a narrow upstairs room at a Materials Research Society meeting in Boston. Simon Middelhoek gave the first paper [37] at what is now counted as *Transducers'81*. A steering committee was formed to plan future international conferences that would be held on odd years; on even years, regional conferences would be held in America, Europe, and Asia. In 1984 the first of these regional meetings in the U.S. was launched at Hilton Head Island, SC *Transducers* and *Hilton Head* continue as major events in the sensor field. The *IEEE MEMS Conference* grew out of the *IEEE Micro Robots and Teleoperators Workshop* [38] held at Hyannis, MA, in 1987, where the acronym "MEMS" was coined. The *IEEE Journal of Microelectromechanical Systems* would not be launched until 1992.

In the US – a Significant Investment from the DoD

From 1992 to 1997, Dr. Gabriel was at the Defense Advanced Research Projects Agency. In 1992, he was recruited to start the Agency's MEMS program and grew the effort to more than $80 million a year with 70+ projects.



DARPA's newest $50 million MEMS initiative

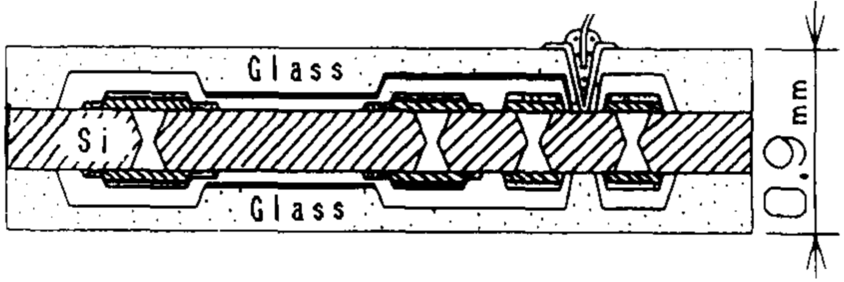
As of July, proposals are in and are now under consideration at DARPA for their newest $50 million MEMS initiative (Issue: PSA 1565, SOL BAA 96-19). Quoting from the BAA: "The long-term goal of DARPA's MEMS program is to merge computation, sensors, actuators, and mechanical structures to radically change the way people and machines interact with the physical world.

Research on MEMS Packaging

ANODIC BONDING FOR INTEGRATED CAPACITIVE SENSORS

M. Esashi, N. Ura, Y. Matsumoto

MEMS 1992



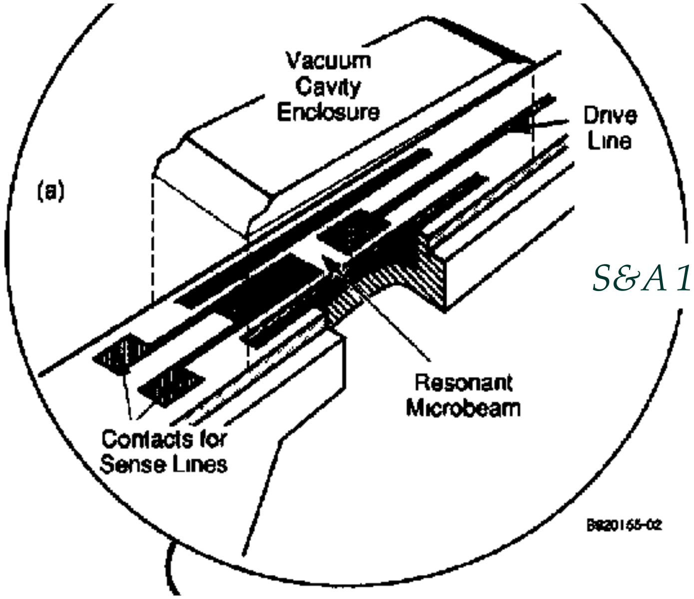
Characteristics of polysilicon resonant microbeams*

J D Zook and D W Burns

Honeywell Sensor and System Development Center, Bloomington, MN 55420 (USA)

H Guckel, J J Sniegowski**, R L Engelstad and Z Feng

Wisconsin Center for Applied Microelectronics, University of Wisconsin, Madison WI 53706 (USA)



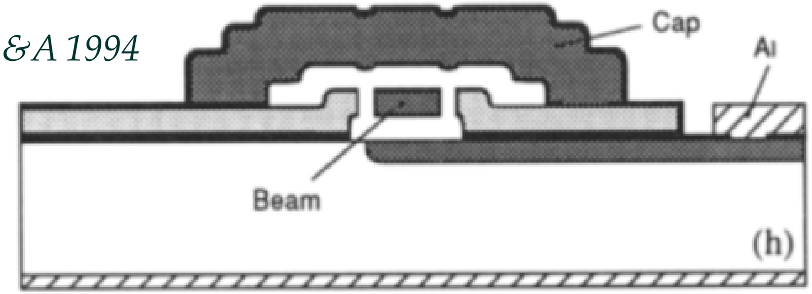
S&A 1992

Electrostatically driven vacuum-encapsulated polysilicon resonators

Rob Legtenberg, Harrie A.C. Tilmans*

MESA Research Institute, University of Twente, PO Box 217, NL-7500 AE Enschede, Netherlands

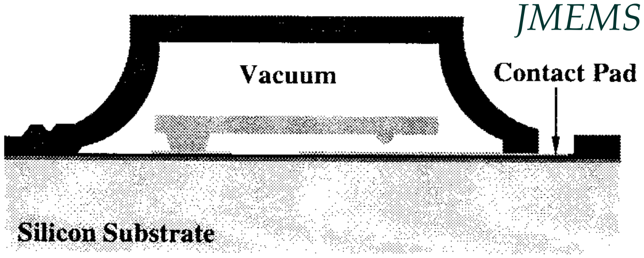
S&A 1994



Microelectromechanical Filters for Signal Processing

Liwei Lin, Roger T. Howe, *Fellow, IEEE,* and Albert P. Pisano

JMEMS 1998



Research on Aging and Reliability

Aging phenomena in heavily doped (p$^+$) micromachined silicon cantilever beams

M. Tabib-Azar, K.Wong and Wen Ko

Sensors and Actuators A, *33* (1992) 199–206

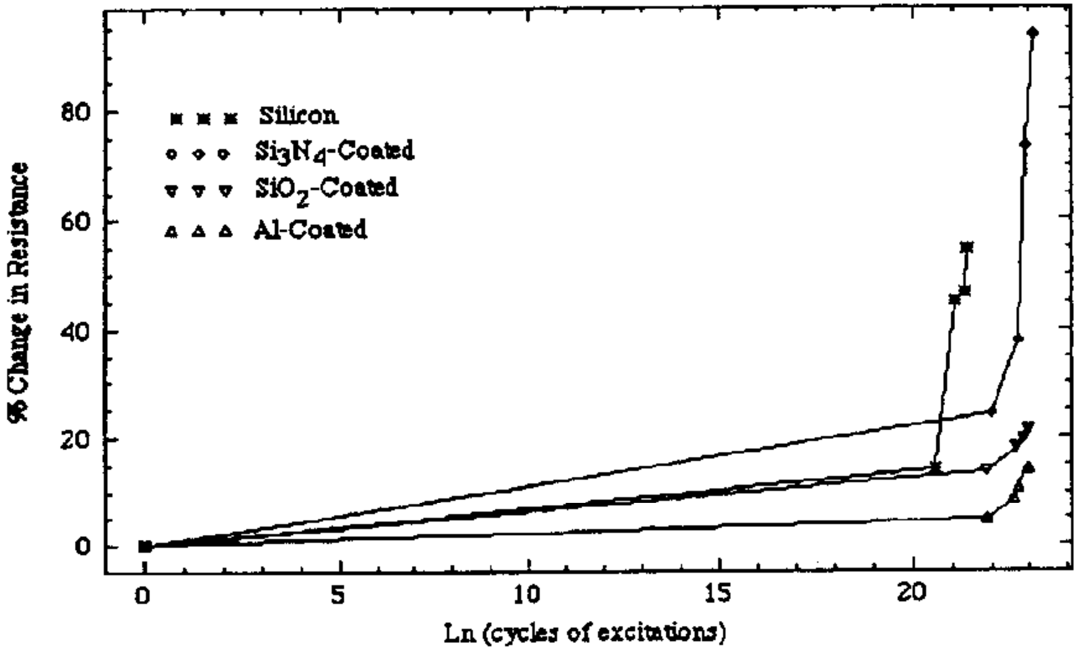


TABLE 1. Mechanical and electrical parameters calculated from the resonance curve of silicon cantilever beams

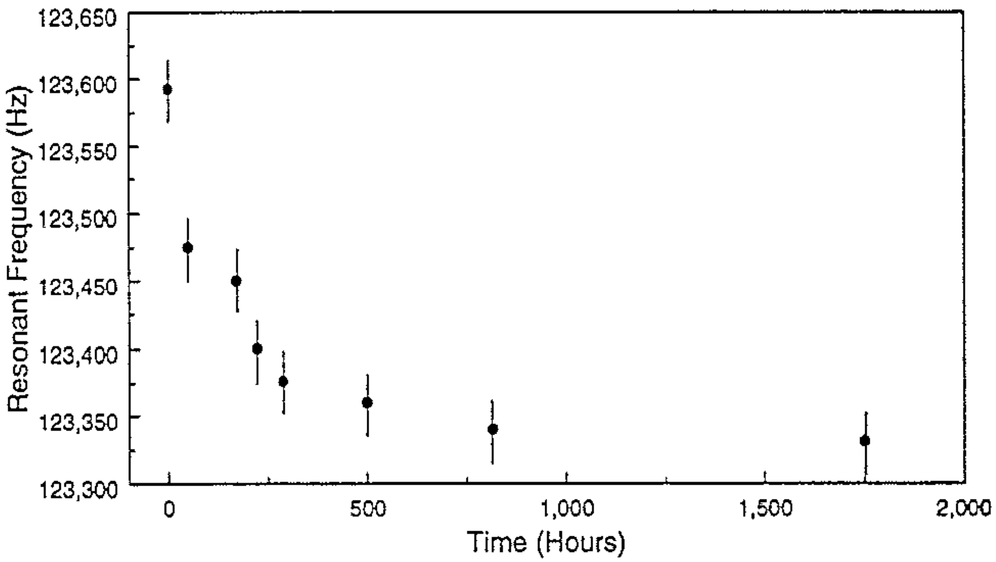
Aging	0	1	2	3	4
Cycle of excitation	0.000E + 00	9.022E + 08	1.464E + 09	1.908E + 09	2.05E + 09
f_0 (kHz)[a]	5.975	6.000	6.025	6.150	6.150
Young's modulus (GPa)[b]	129	130	131	136	136
Damping coeff. (Hz)	600.84	644.69	730.12	749.56	769.74

Research on Aging and Reliability

Long-term stability of silicon bridge oscillators fabricated using the boron etch stop

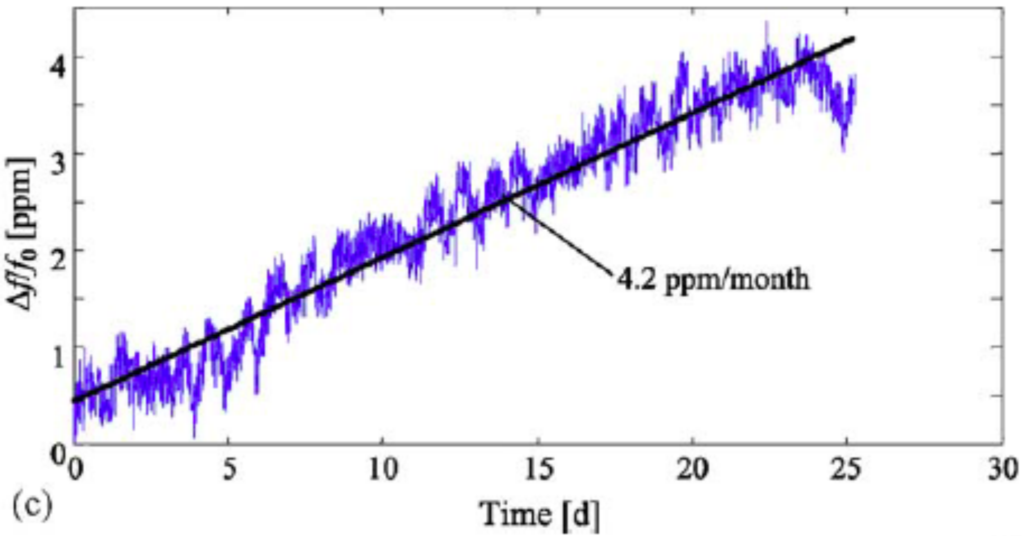
Andrew Pember [a], Jim Smith [b], Henri Kemhadjian [b]

Sensors and Actuators A 46–47 (1995) 51–57



The basic implication of this work is that the long-term stability of sensors based on such structures should be very good, provided that a ‘burn in’ or maturing period is observed before calibration and use of the device. The exact mechanism of ageing is not clear

Research on Aging and Reliability

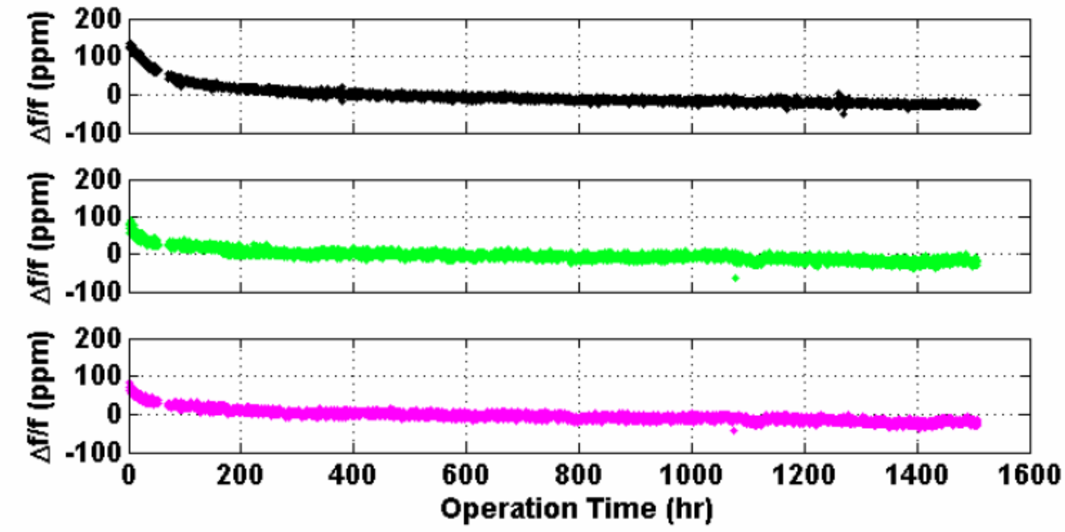


Stability of wafer level vacuum encapsulated single-crystal silicon resonators

Ville Kaajakari[a,*], Jyrki Kiihamäki[a], Aarne Oja[a], Sami Pietikäinen[b], Ville Kokkala[b], Heikki Kuisma[b]

Sensors and Actuators A 130–131 (2006) 42–47

Results from a cantilever beam sealed in wafer-level package using commercial-style anodic bonding



MEMS RESONATORS IN CMOS COMPATIBLE WAFER-SCALE ENCAPSULATION

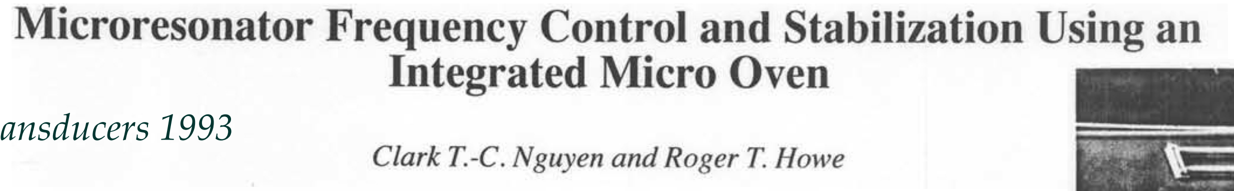
B. Kim, M. Hopcroft, R. Melamud, C. Jha, M. Agarwal,
S. Chandorkar and T.W. Kenny

Proceedings of IPACK2007
ASME InterPACK '07
July 8-12, 2007, Vancouver, British Col μmbia, CANADA

Results from a tuning fork encapsulated using CVD Low-Temperature Oxide for final sealing step

OK for Inertial Sensors; Not Good Enough for Resonators

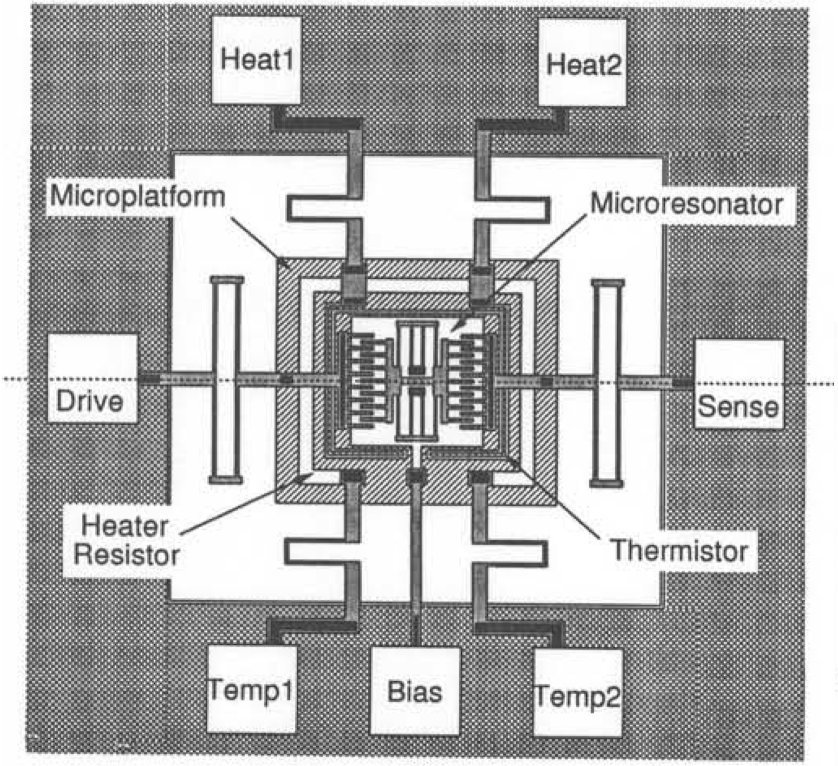
Research on Temperature Control



Microresonator Frequency Control and Stabilization Using an Integrated Micro Oven

Transducers 1993

Clark T.-C. Nguyen and Roger T. Howe



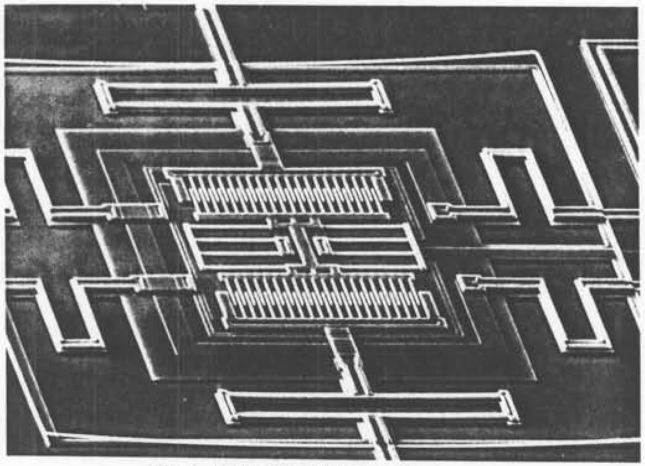
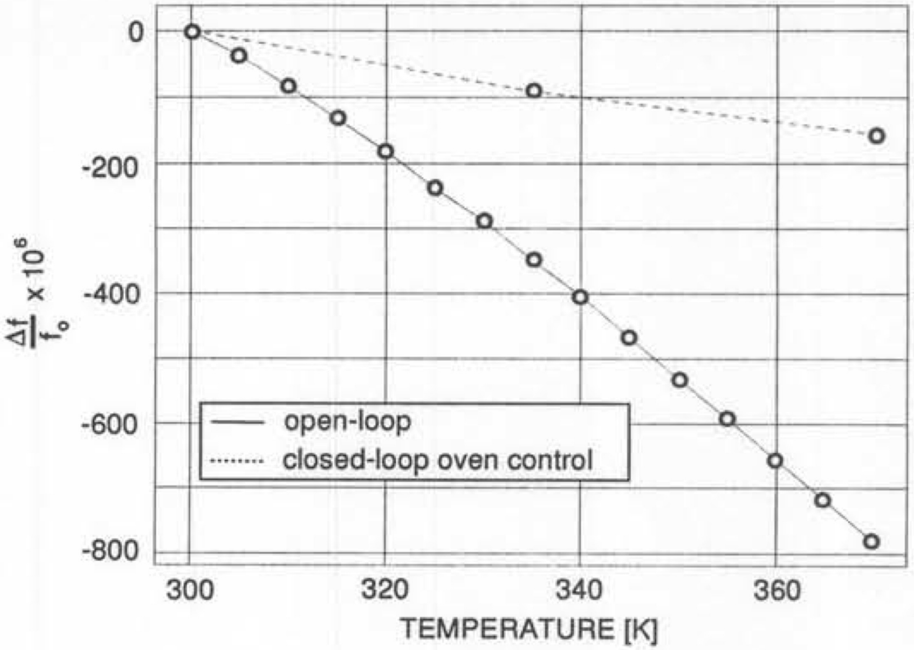


Fig 5. SEM of a fabricated micro-oven



By 2000, We Still Couldn’t Make Stable MEMS Resonators

MEMS Resonators need a Vacuum Package

Low pressure required for high Q.

Package must be Compact and Hermetic.

All related to Packaging

MEMS Resonators Suffered from Aging

Many observations of drift, “burn-in”, fatigue.

MEMS Reliability Research just beginning

MEMS Resonators have too much F(Temperature)

30 ppm/C is too large for timing applications.

Compensation not practical.

Wafer-Scale Encapsulation Process for Inertial Sensors

Proposed in 1999 by Markus Lutz, of Bosch RTC.

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

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

BOSCH

What is the Encapsulation Process?

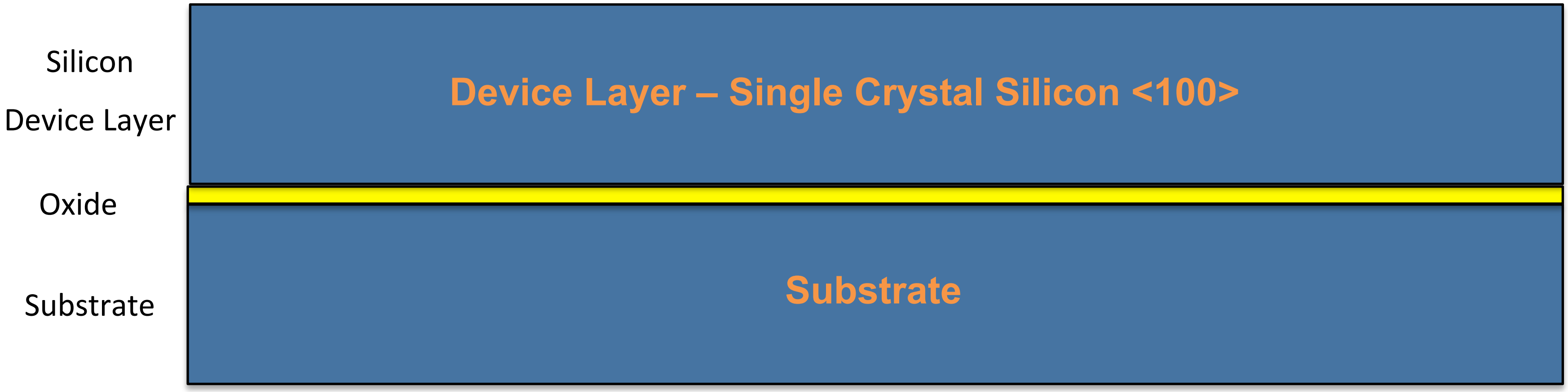
Start with Standard <100> Silicon Wafer

- Device layer can be ~3 um to 60 um

SiTime It's about time BOSCH

Stanford University

DARPA


Silicon

Device Layer

Device Layer – Single Crystal Silicon <100>

Oxide

Substrate

Substrate

What is the Encapsulation Process?

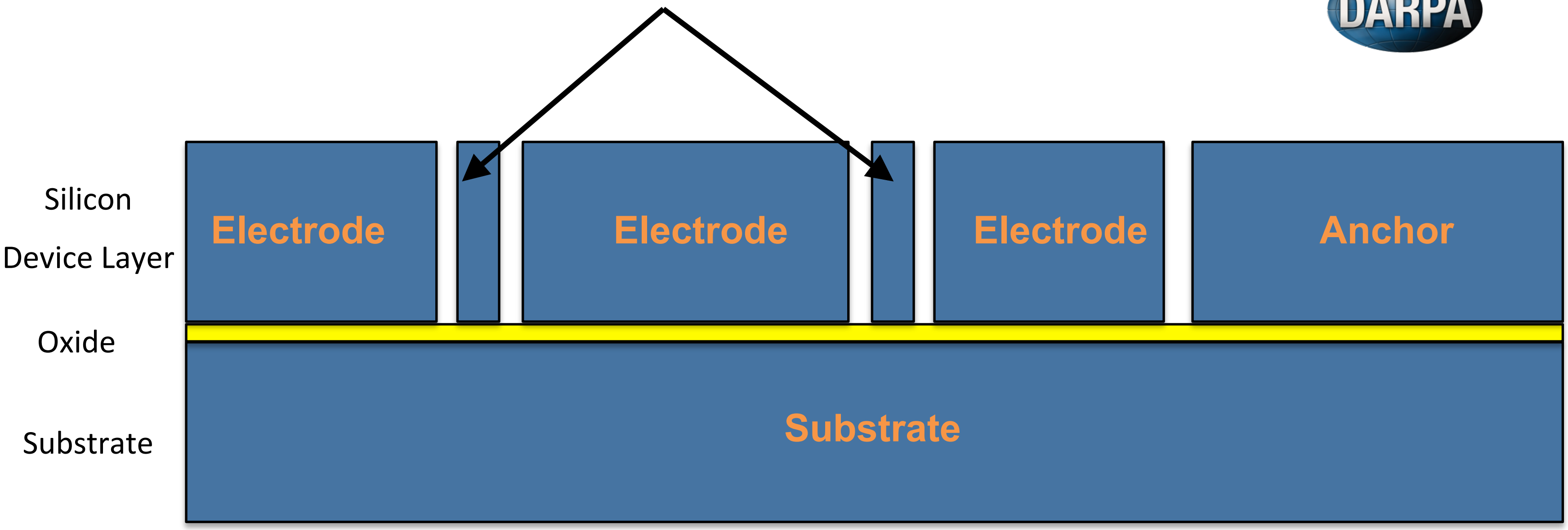
Plasma Etch trenches from surface down to buried oxide

- Define Electrodes, Anchors and Moving elements

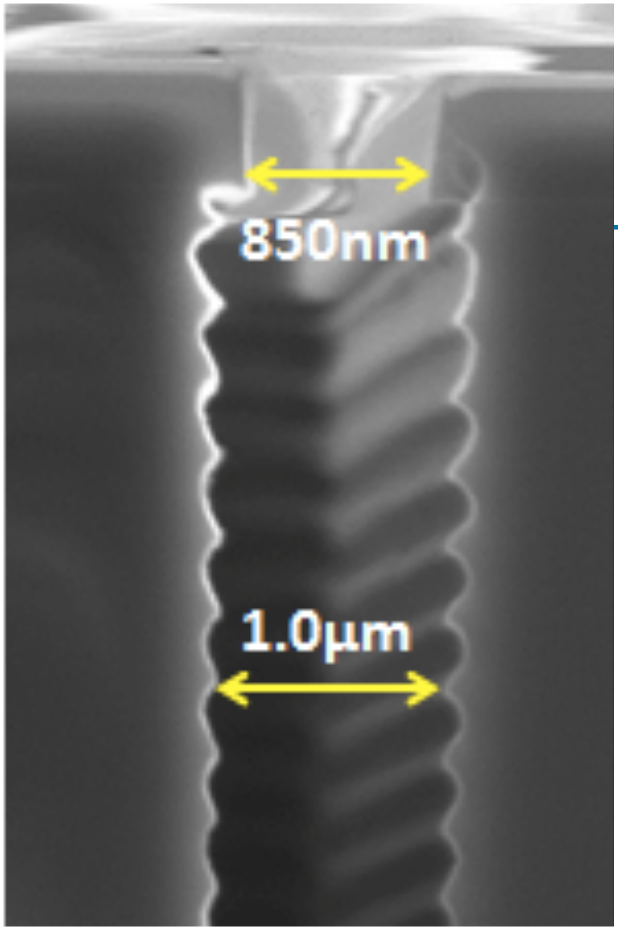
SiTime It's about time BOSCH

Stanford University

DARPA



Top of trench



SiTime It's about time BOSCH

Stanford University

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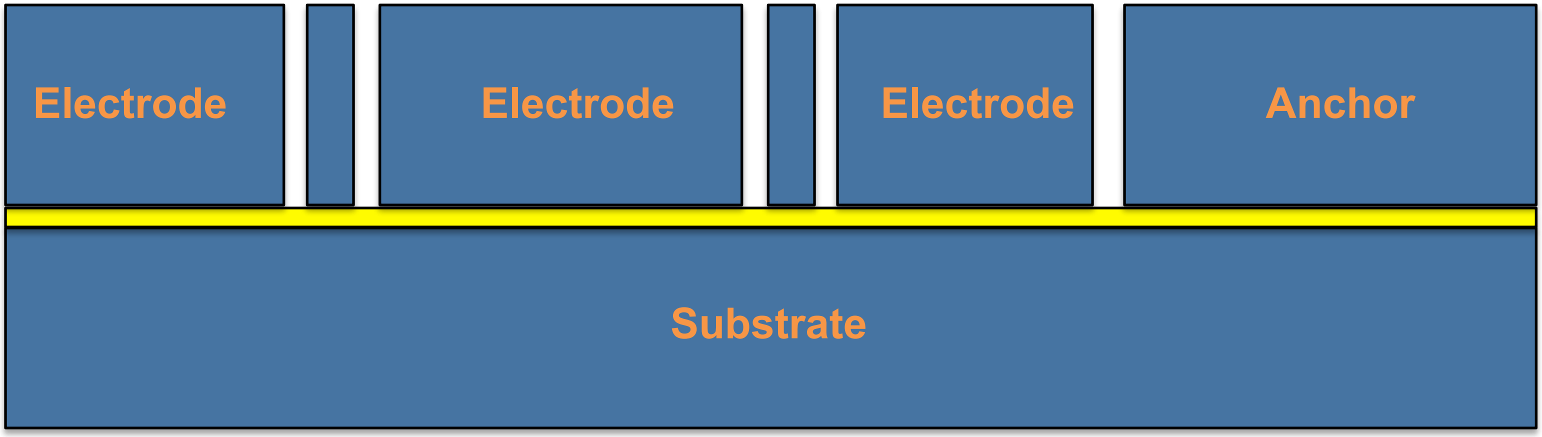


Silicon Device Layer

Oxide

Substrate

Electrode

Electrode

Electrode

Anchor

Substrate

What is the Encapsulation Process?

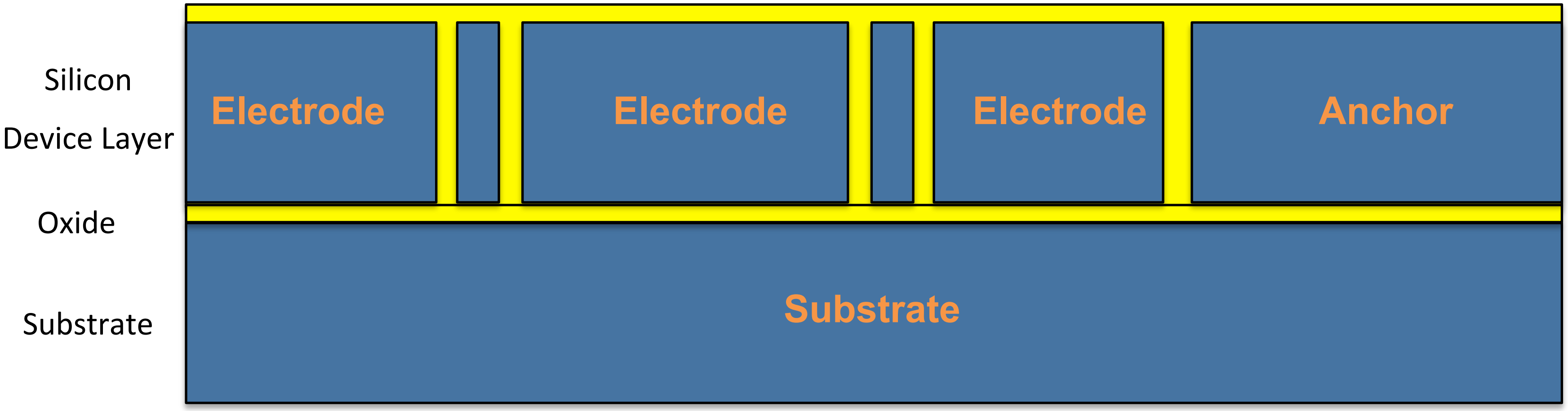
Fill trenches and cover with SiO2

- Can be LPCVD SiO2, TEOS
- Oxide doesn’t need to completely fill, but must completely cover

SiTime BOSCH

Stanford University

DARPA



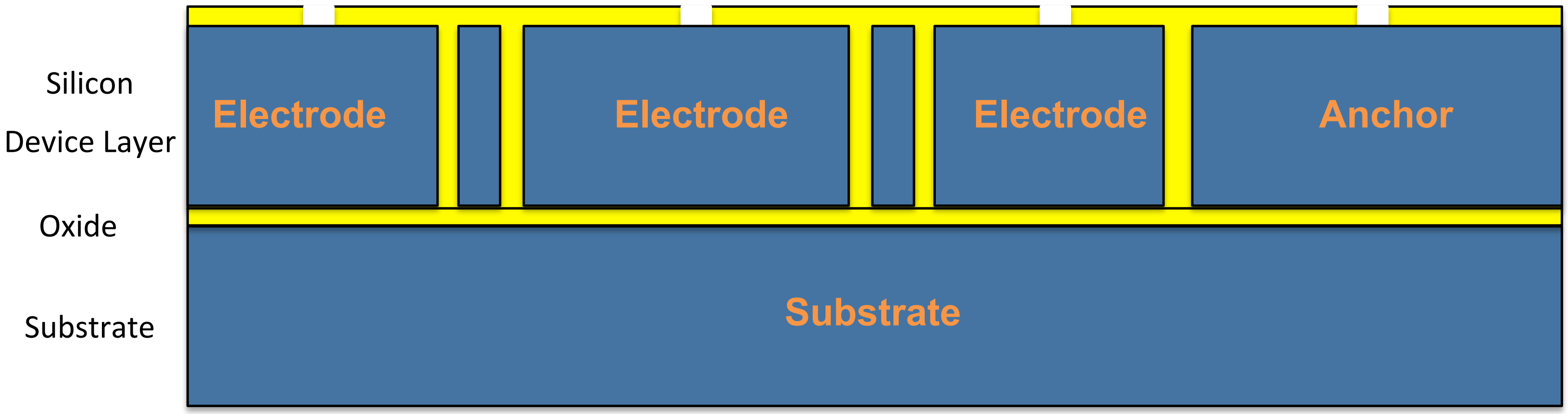
What is the Encapsulation Process?

Fill trenches and cover with SiO2

- Can be LPCVD SiO2, TEOS
- Oxide doesn't need to completely fill, but must completely cover

Etch a few contacts through SiO2

SiTime BOSCH
Stanford University
DARPA



What is the Encapsulation Process?

Grow first layer of package ~ 3 um fine grain epi-poly

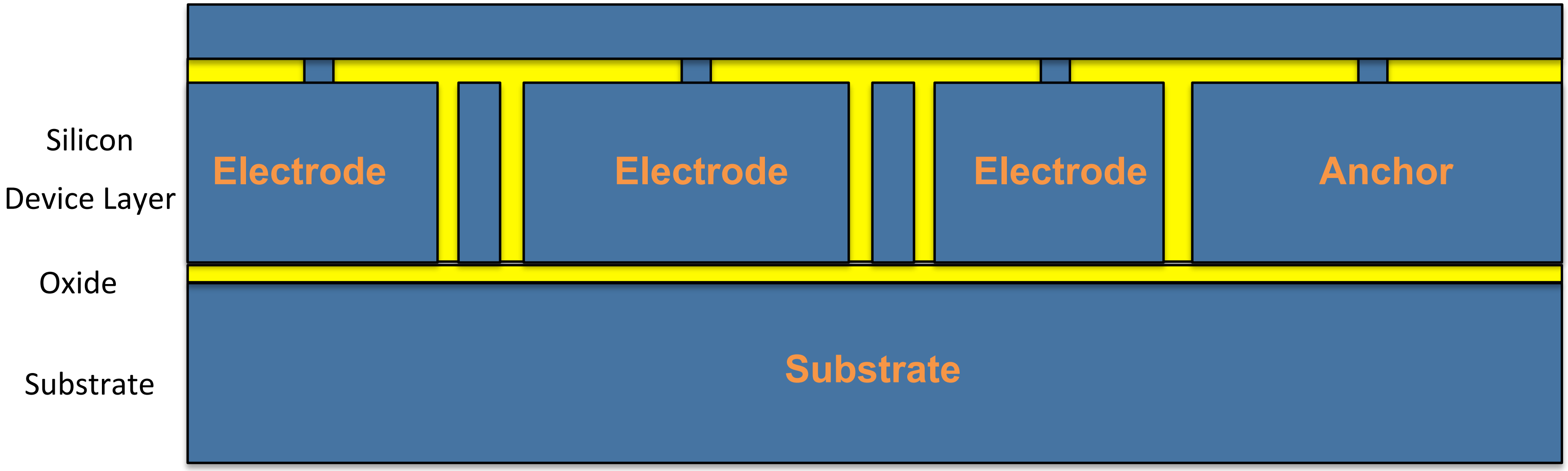
- Bosch epi-poly used as device layer in all MEMS products
- Low stress, stable mechanical properties

CMP process to smooth top surface topography

DARPA

SiTime It's about time BOSCH

Stanford University



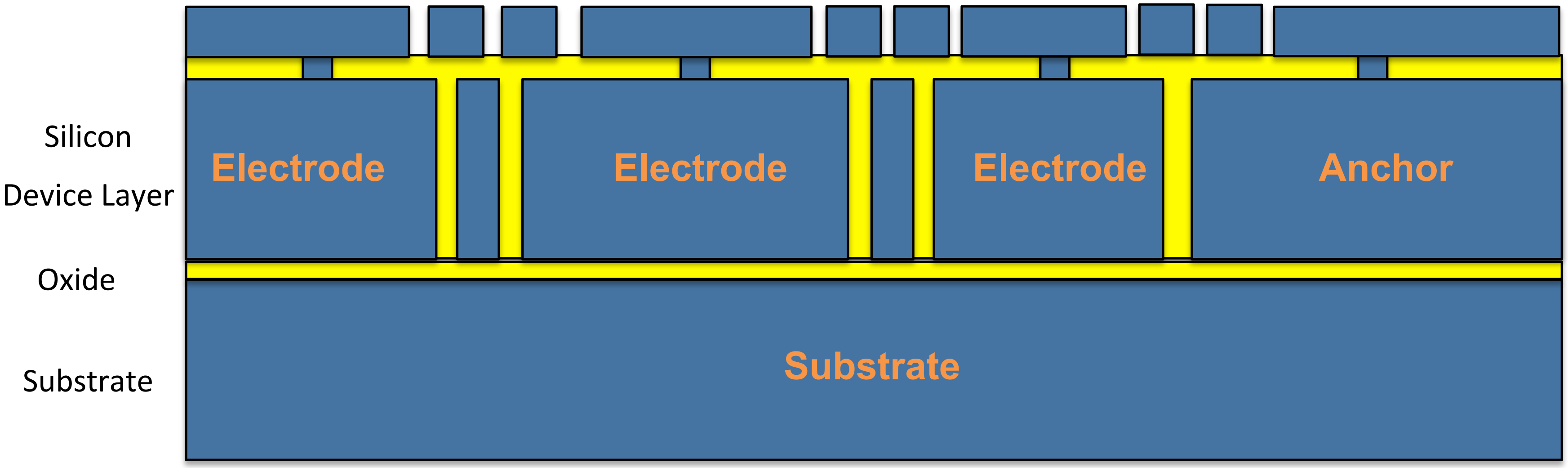
What is the Encapsulation Process?

Plasma Etch openings through first cap where devices are to be released

- Placement not critical
- Opening sizes ~ 0.7 um

SiTime BOSCH

Stanford University



What is the Encapsulation Process?

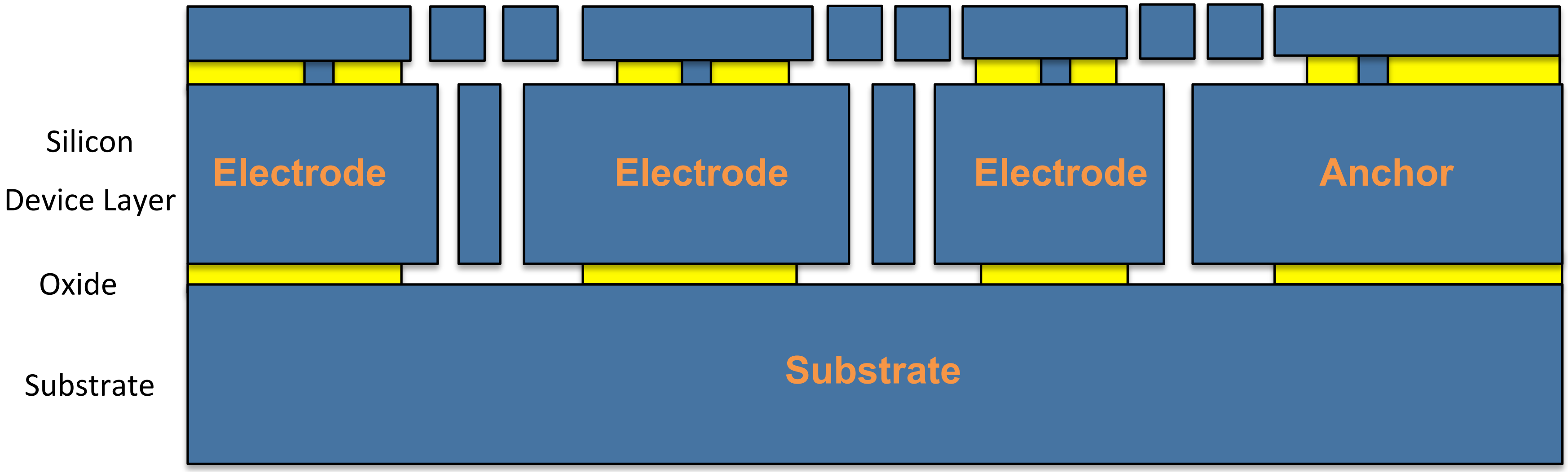
HF Vapor Tech to remove SiO2 around elements to be released

- Placement of released structures relative to fixed structures is important. Design Rules matter!
- HF Vapor Etch now available from Vendors and Foundries

DARPA

SiTime It's about time BOSCH

Stanford University



What is the Encapsulation Process?

Seal parts in Epitaxial Reactor

- **1100 C process in ultra clean chamber**
- Exposure to H_2 at 1100C causes extreme sidewall smoothing
- After process, H_2 gas remains at ~10 torr
- H_2 removed by 450C annealing in N_2 furnace

DARPA

SiTime It's about time BOSCH

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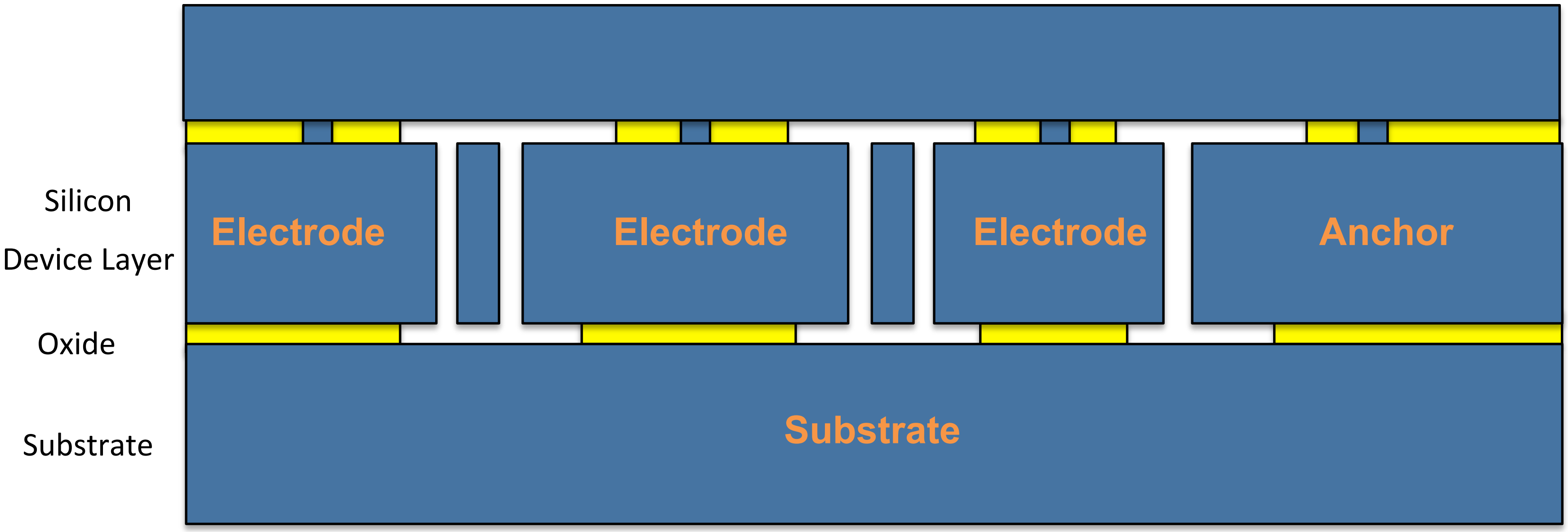
CMP to remove topography after growth.



What is the Encapsulation Process?

Electrical Contacts

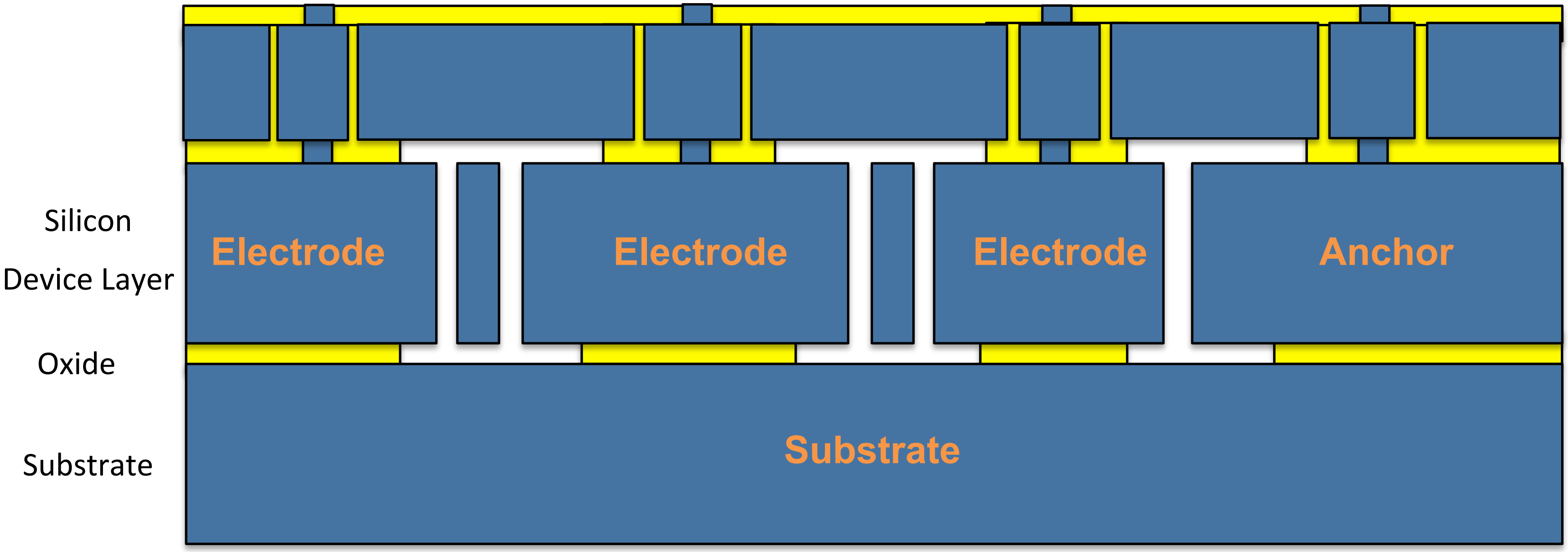
- Etch Annular trenches around contact plugs
- refill with SiO2 and Passivate
- Deposit Al Metal and pattern
- Dice, mount and package

All of this can happen in any CMOS fab

DARPA

SiTime It's about time BOSCH

Stanford University

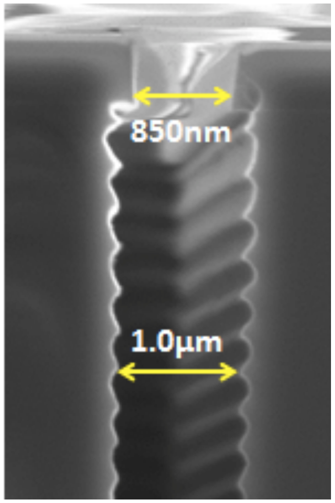


What is the Encapsulation Process?

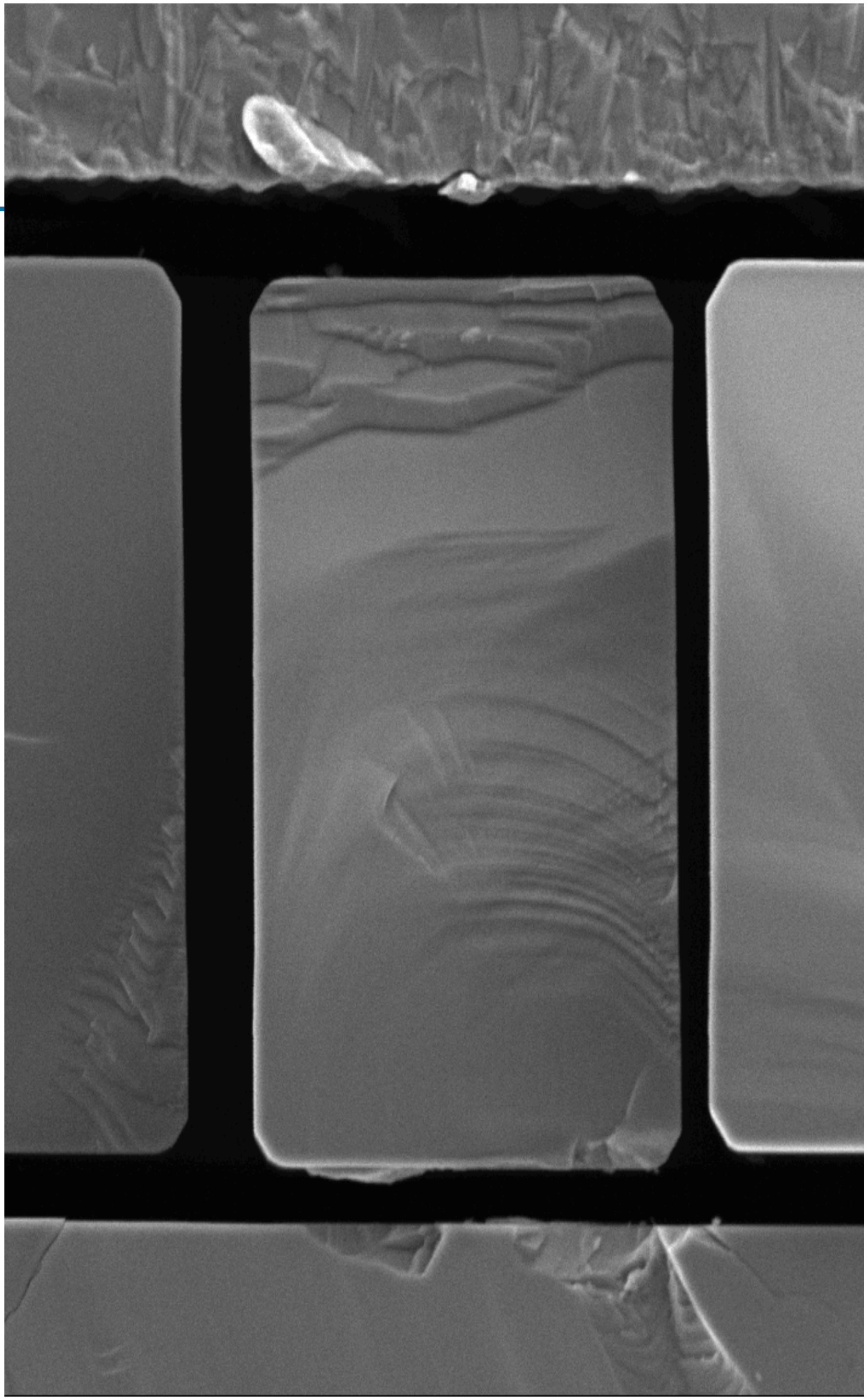
High-Temp Encapsulation – Many Beneficial Features

No native oxide
No adhering species
No outgassing

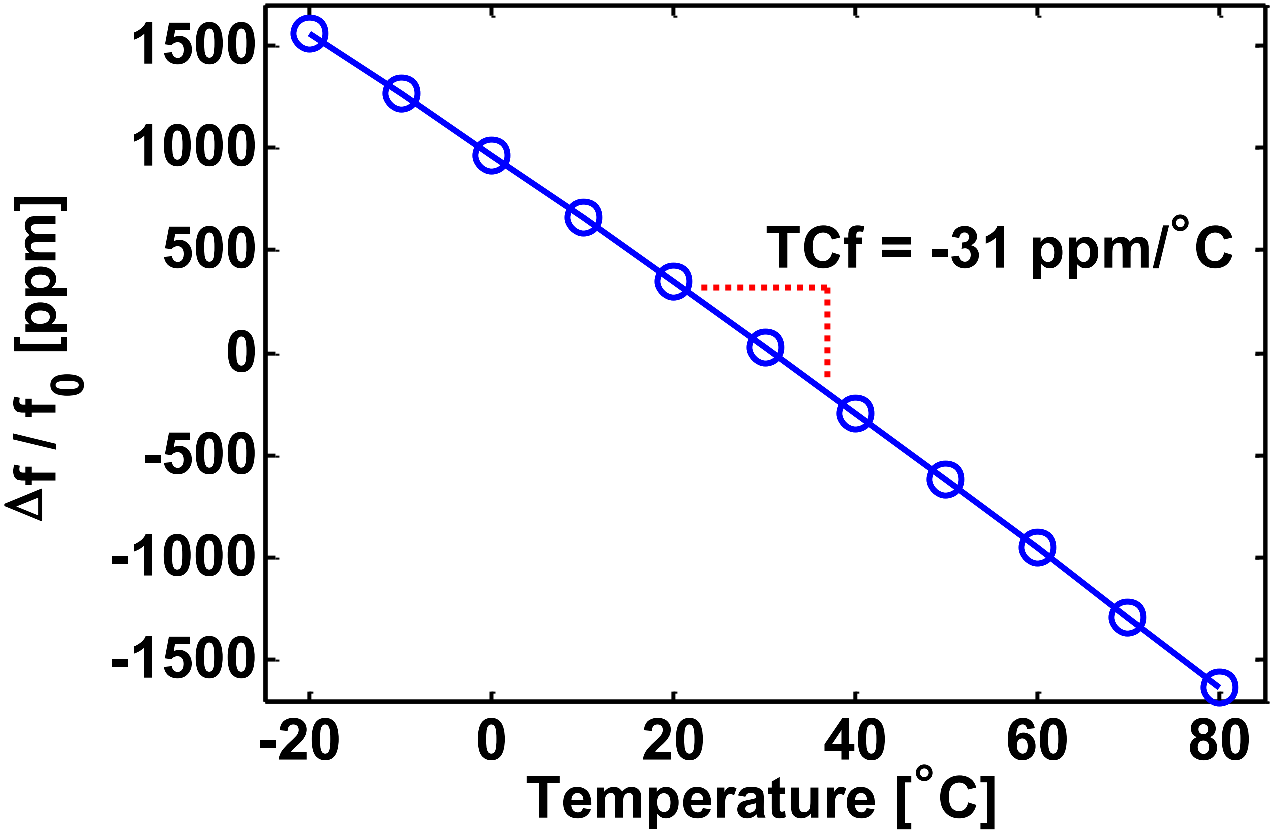
No surface relaxation
No stress concentrations
No fatigue
No aging



Top of trench



Temperature Sensitivity of Silicon Resonators



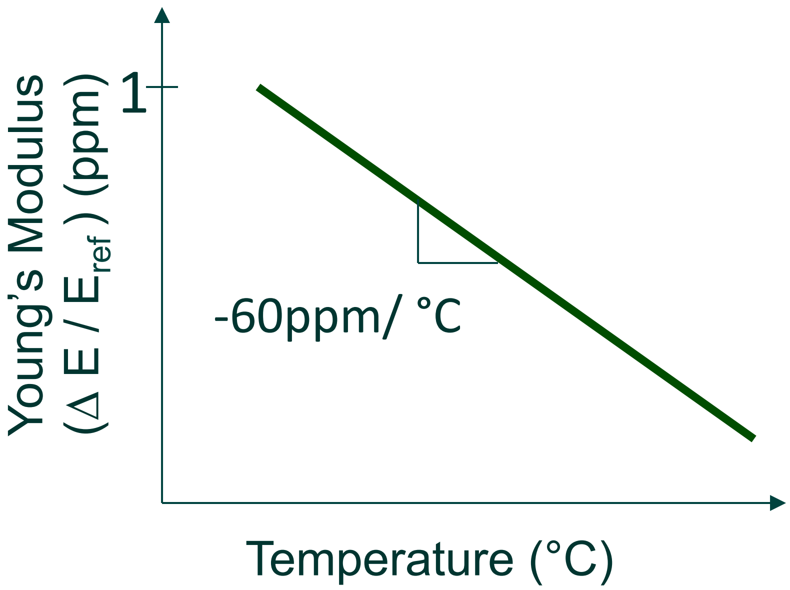
Dominated by temperature dependence of Elastic Modulus

Small contribution from Thermal Expansion

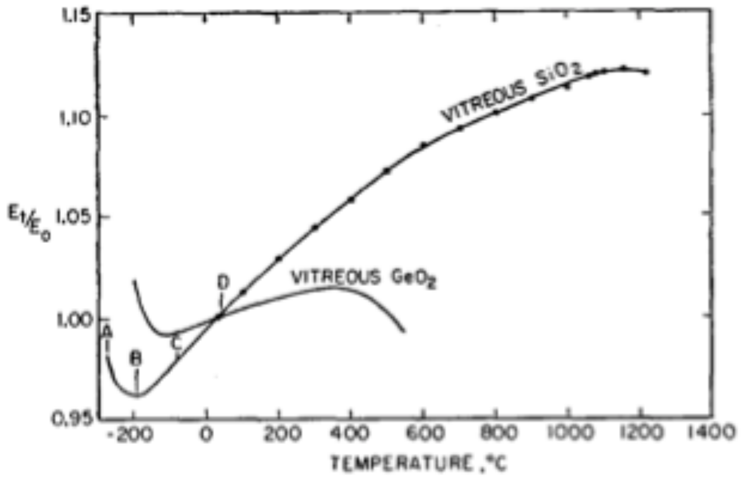
100X worse than Quartz!

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.

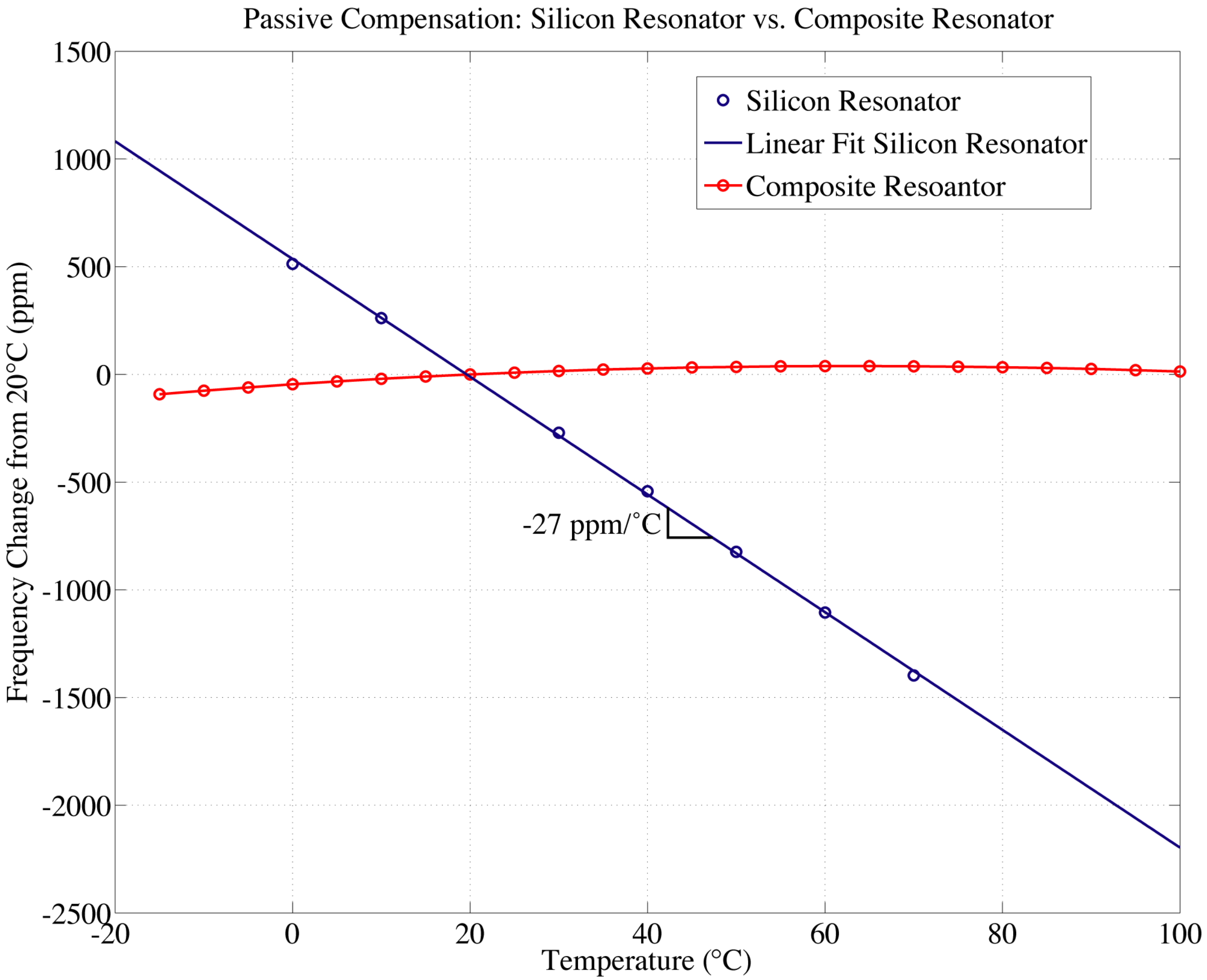
- **Silicon becomes softer with increase in temperature**
- **Silicon dioxide (SiO_2) becomes stiffer as temperature increases**
- **Combination of Si and SiO_2 will compensate resonant frequency change due to temperature change**
- **SiO2 can be added to our fabrication sequence.**

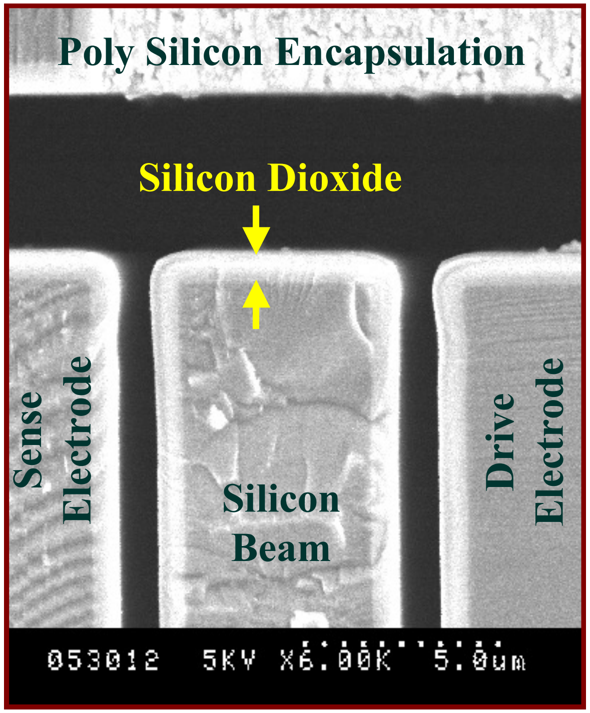
JOURNAL OF MICROELECTROMECHANICAL SYSTEMS, VOL. 18, NO. 6, DECEMBER 2009 1409

STANFORD
UNIVERSITY

Temperature-Insensitive Composite Micromechanical Resonators

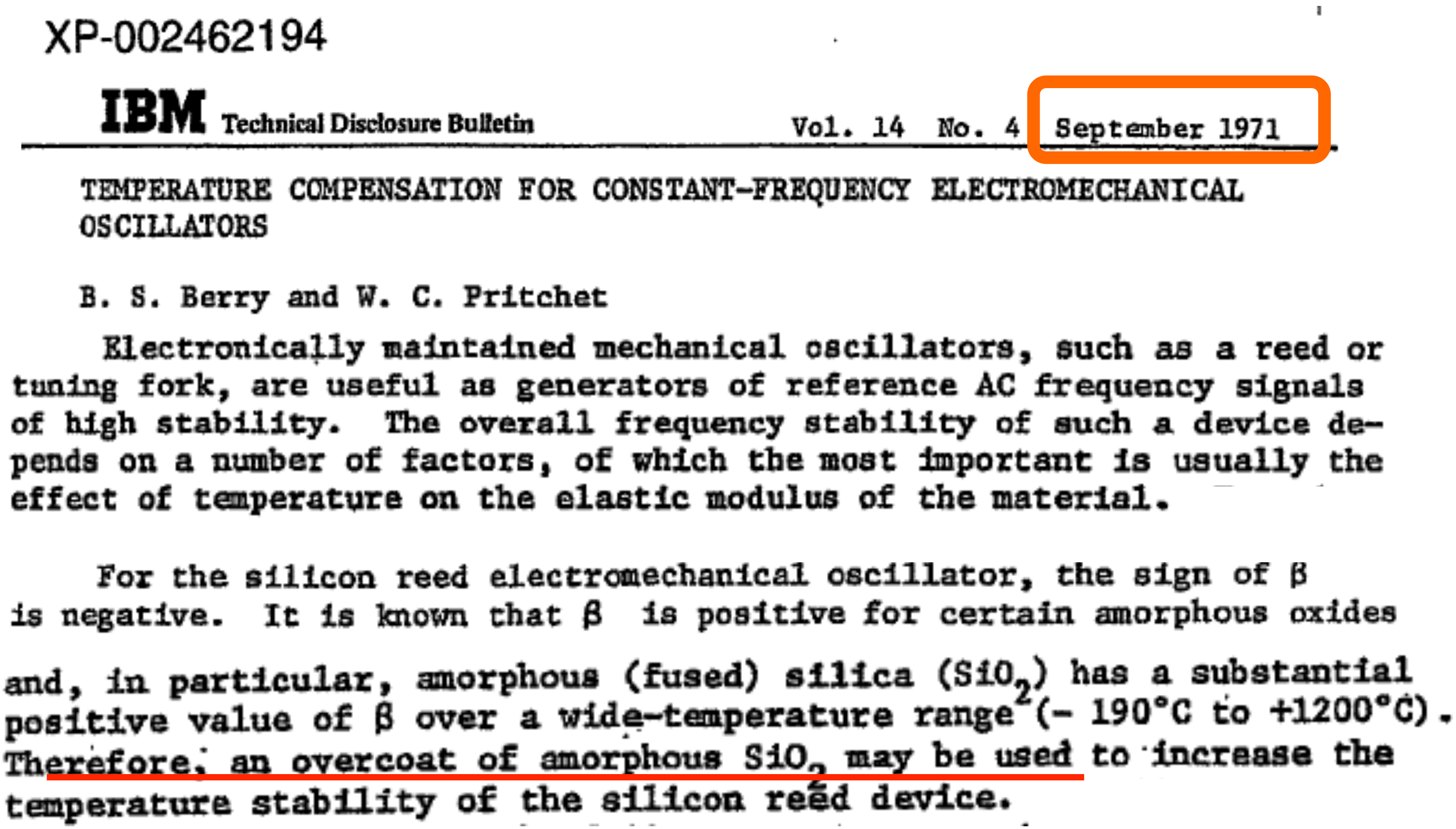
Renata Melamud, *Member, IEEE*, Saurabh A. Chandorkar, Bongsang Kim, *Member, IEEE*,
Hyung Kyu Lee, James C. Salvia, *Student Member, IEEE*, Gaurav Bahl,
Matthew A. Hopcroft, *Member, IEEE*, and Thomas W. Kenny





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

Very Fast Early Progress!



XP-002462194

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

TEMPERATURE COMPENSATION FOR CONSTANT-FREQUENCY ELECTROMECHANICAL OSCILLATORS

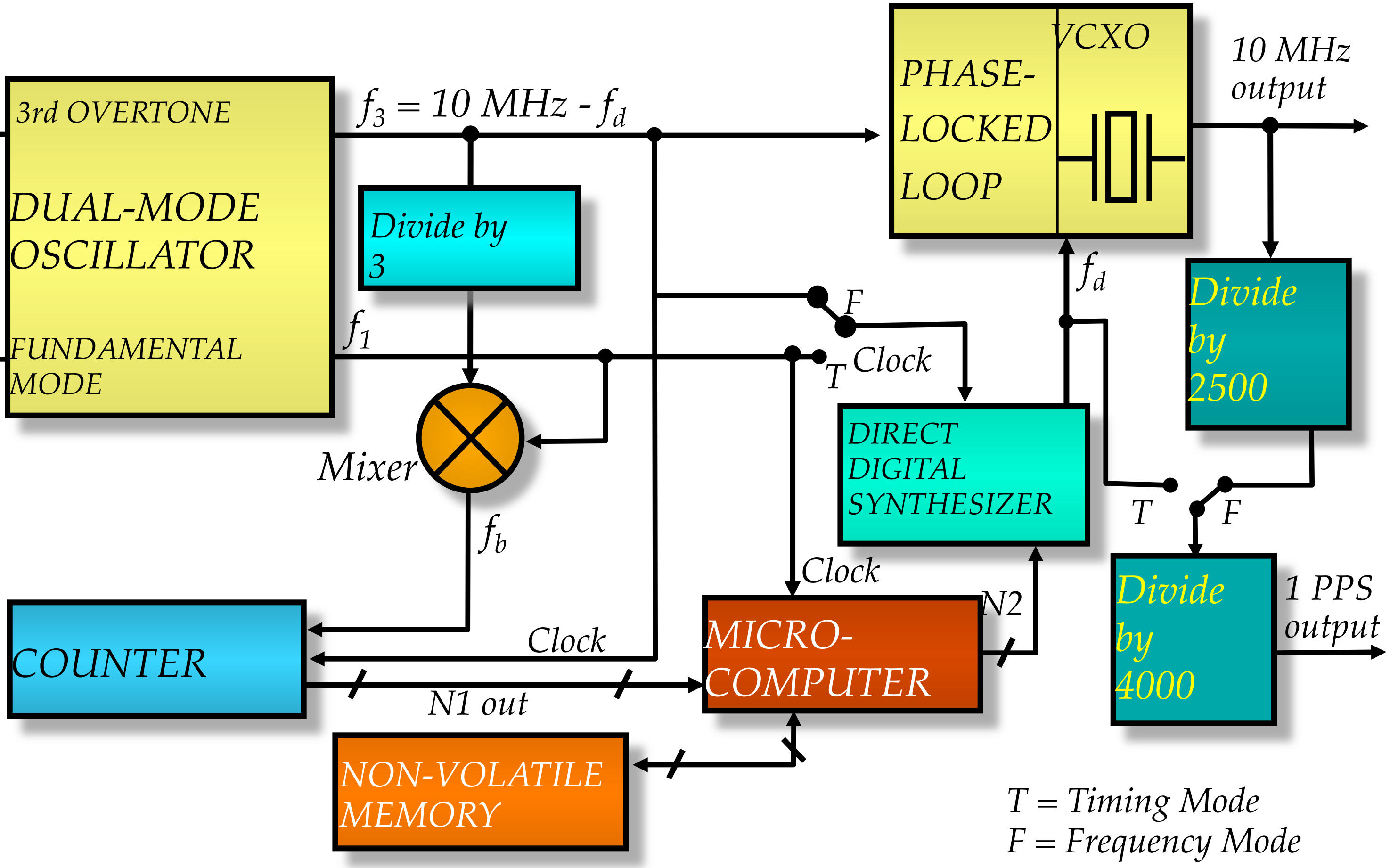
B. S. Berry and W. C. Pritchet

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.

MCXO Frequency Summing Method

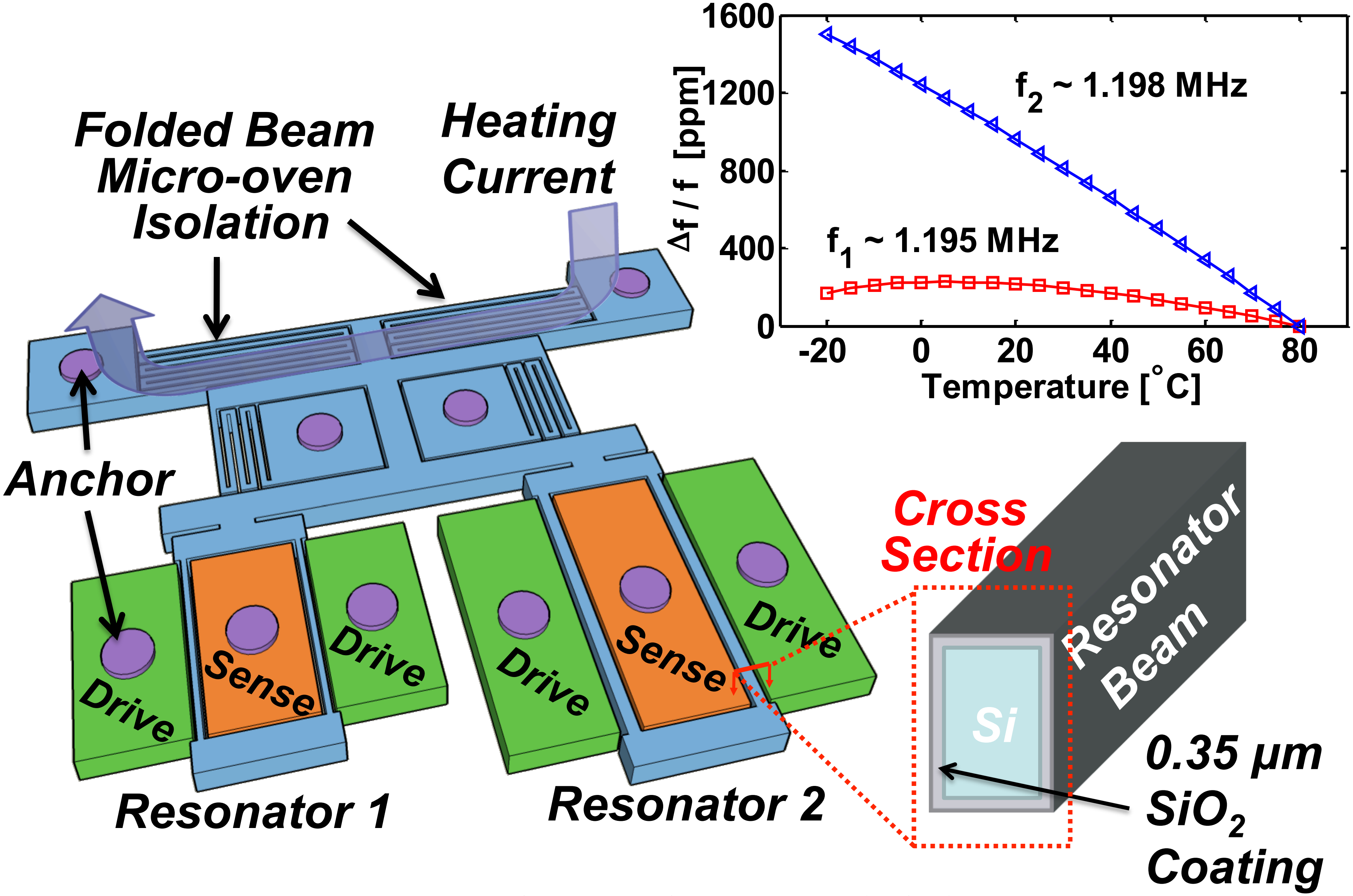
Block Diagram



T = Timing Mode
F = Frequency Mode

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



Folded Beam Micro-oven Isolation

Heating Current

Anchor

Resonator 1

Resonator 2

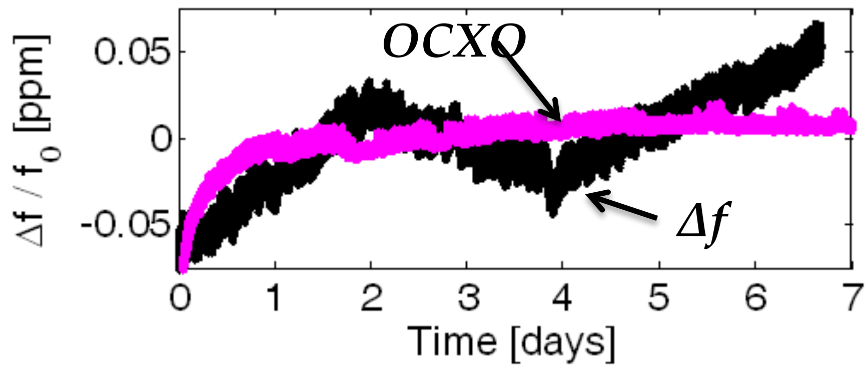
Cross Section

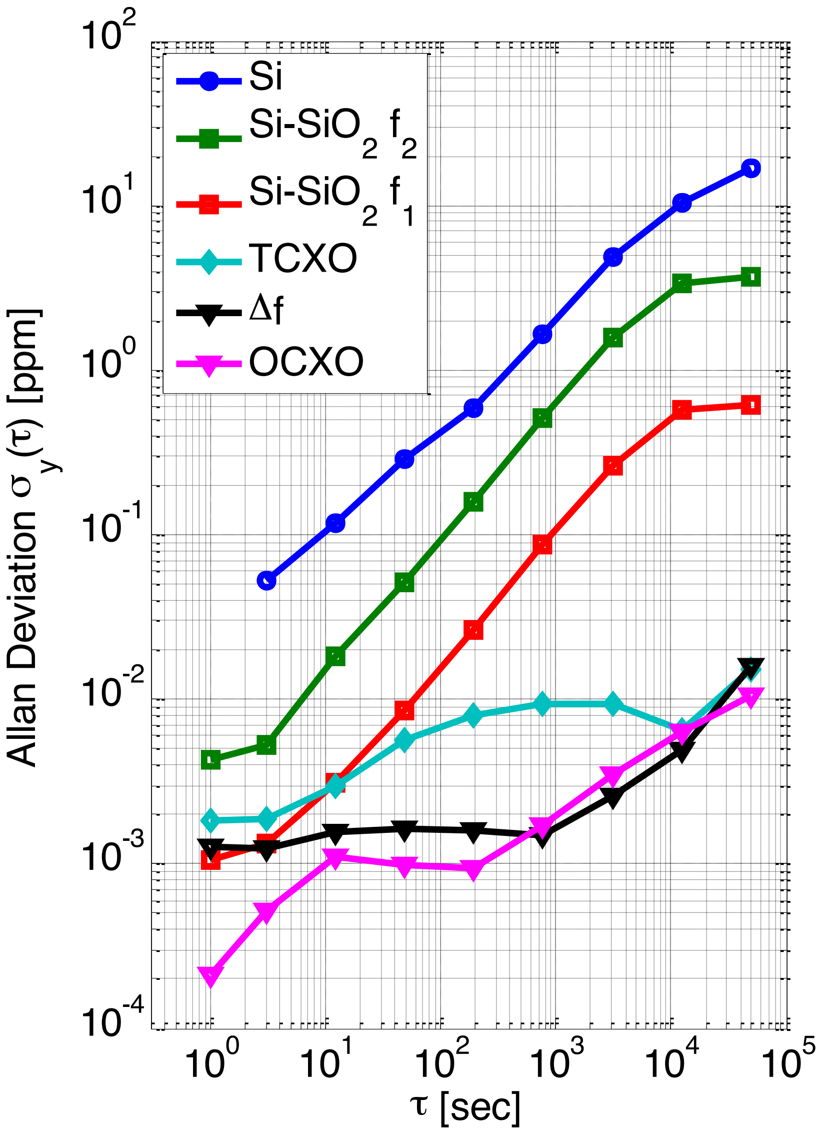
Resonator Beam

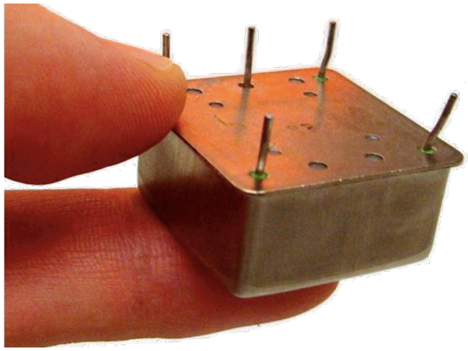
0.35 µm SiO_2 Coating

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

Oscillator Stability Comparison







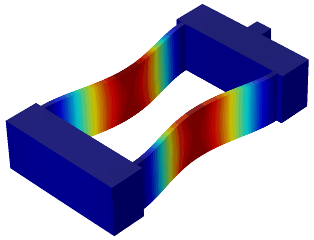
Quartz OCXO
Vectron (Corning) C4550 100 MHz

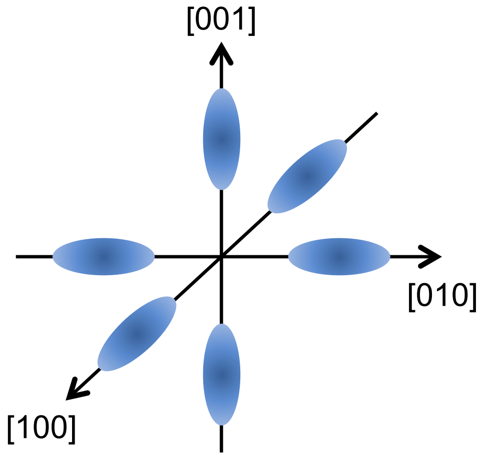
STANFORD
UNIVERSITY

Heavy doping for Temperature Compensation

Proposed Mechanism: Free Charge Carrier Effect

- Acoustic vibrations strain the crystal lattice
- Strain shifts the energy bands by the deformation potential effect
- Charge carriers in the raised valleys transfer to lower energy valleys to minimize free energy
- Lowered free energy (due to charge carrier effects) results in a decrease in elastic constants that is temperature dependent





Silicon constant energy ellipsoids near the conduction band minima

$$C_{ij} = \frac{1}{V}\frac{\partial^2 F}{\partial \varepsilon_i \partial \varepsilon_j}$$

$$\delta C_{11} = -\frac{2n\Xi_u^2}{9E_F}\left(\frac{\eta F'_{1/2}(\eta)}{F_{1/2}(\eta)}\right)$$

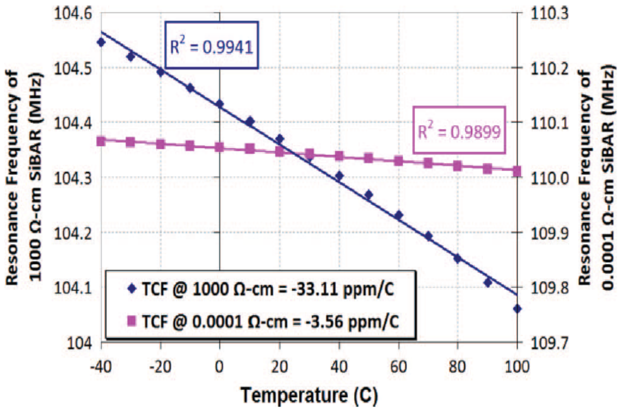
$$\delta C_{12} = \frac{n\Xi_u^2}{9E_F}\left(\frac{\eta F'_{1/2}(\eta)}{F_{1/2}(\eta)}\right)$$

Temperature Dependent!

R. W. Keyes, Solid State Physics 20, pp. 37-90, 1967

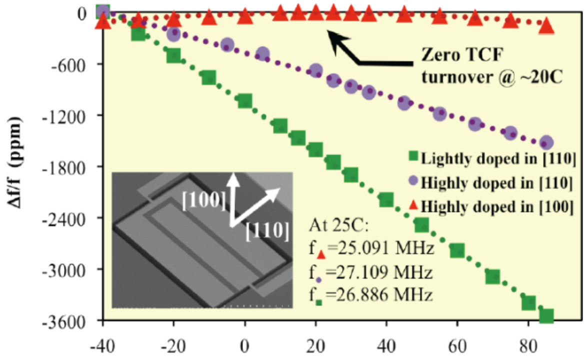
Doped Silicon Devices Exhibit Reduced TCF

Boron ~E20

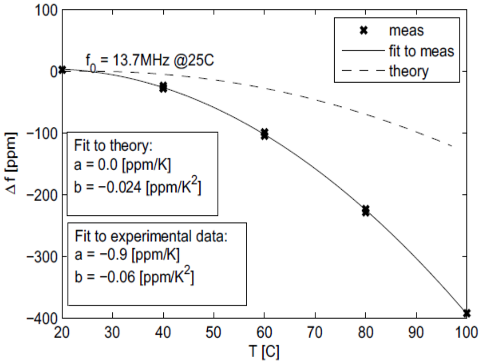


Samarao & Ayazi, Trans. Elec. Dev. 59 1, 2012 (GeorgiaTech)

Phosphorus ~5E19



Shahmohammadi et al., Freq. Ctrl. Symp. 2012 (Oklahoma State University)



Pensala et al., Ultrasonics Symp. 2011 (VTT, Finland)

- Heavily doped silicon reduces the temperature sensitivity of silicon
- Temperature dependence varies with dopant type, level, and geometry
- Need a predictive model for the temperature dependence of doped silicon resonators

Temperature Dependence of Elastic Constants

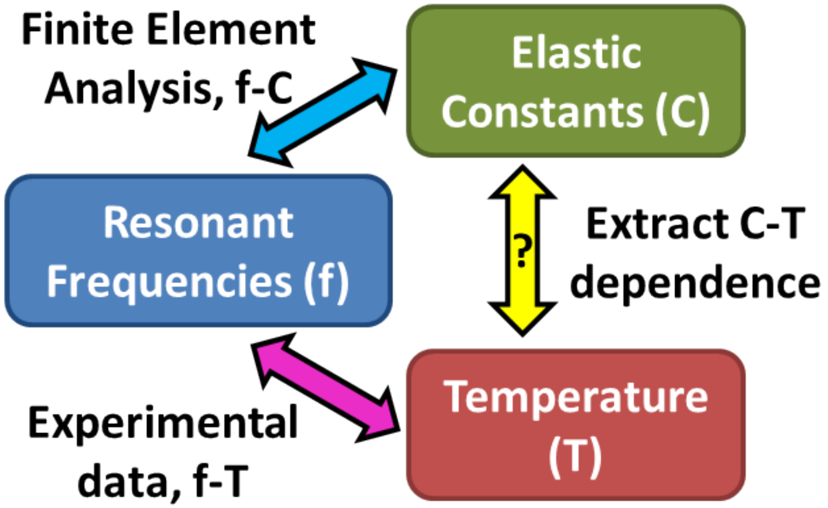
Silicon: Orthotropic in <100>

Elastic matrix $\boldsymbol{C}$

$$\begin{bmatrix}\sigma_1\\\sigma_2\\\sigma_3\\\sigma_4\\\sigma_5\\\sigma_6\end{bmatrix}=\begin{bmatrix}\boldsymbol{c_{11}} & \boldsymbol{c_{12}} & c_{12} & 0 & 0 & 0\\ c_{12} & c_{11} & c_{12} & 0 & 0 & 0\\ c_{12} & c_{12} & c_{11} & 0 & 0 & 0\\ 0 & 0 & 0 & \boldsymbol{c_{44}} & 0 & 0\\ 0 & 0 & 0 & 0 & c_{44} & 0\\ 0 & 0 & 0 & 0 & 0 & c_{44}\end{bmatrix}\begin{bmatrix}\varepsilon_1\\\varepsilon_2\\\varepsilon_3\\\varepsilon_4\\\varepsilon_5\\\varepsilon_6\end{bmatrix}$$

$$\boldsymbol{S} = \boldsymbol{C}^{-1}$$

Compliance   Elastic matrix



Finite Element Analysis, f-C

Elastic Constants (C)

Resonant Frequencies (f)

Extract C-T dependence

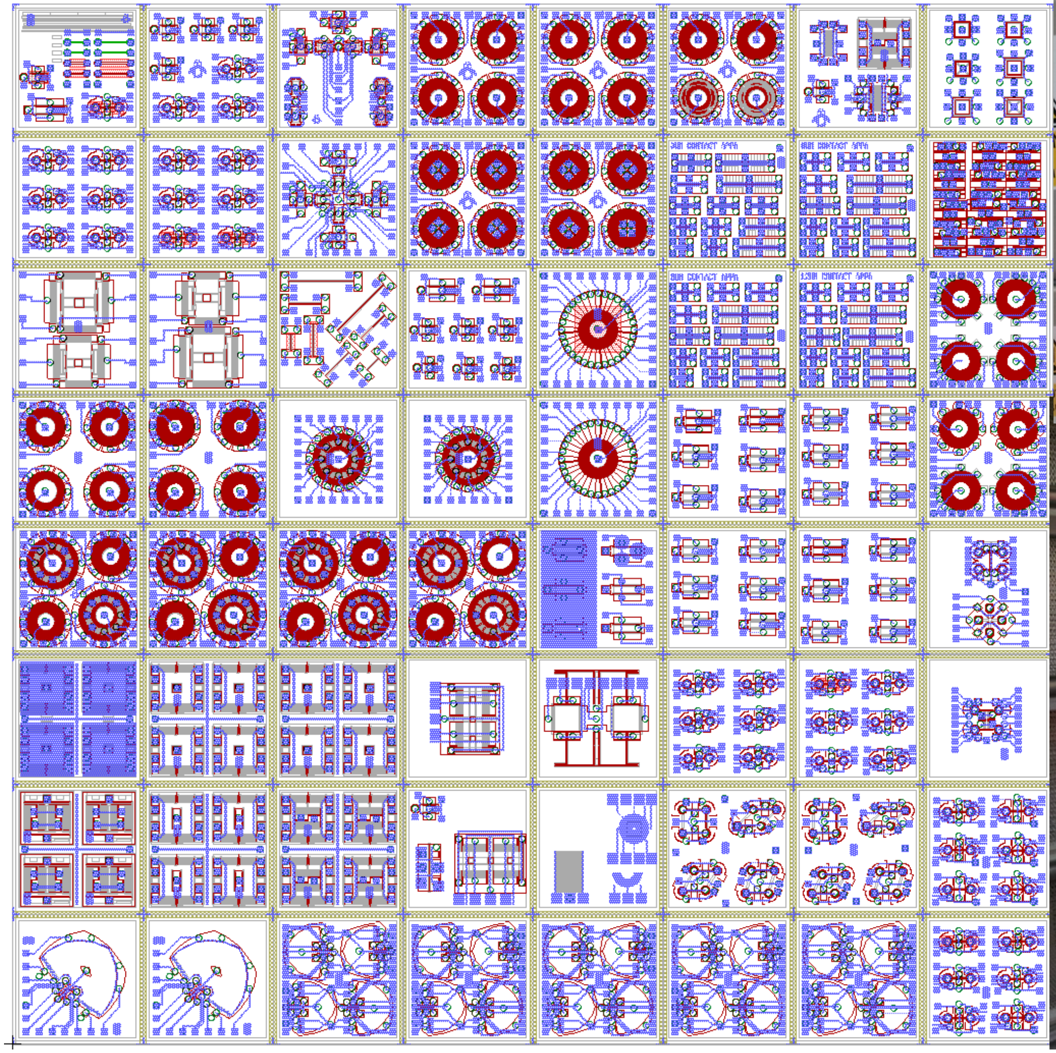
Experimental data, f-T

Temperature (T)

- Use experimental data to obtain frequency-temperature dependence
- Use Finite Element Analysis to relate resonant frequency to elastic constants
- Extract the elastic constants ‘ dependence on temperature

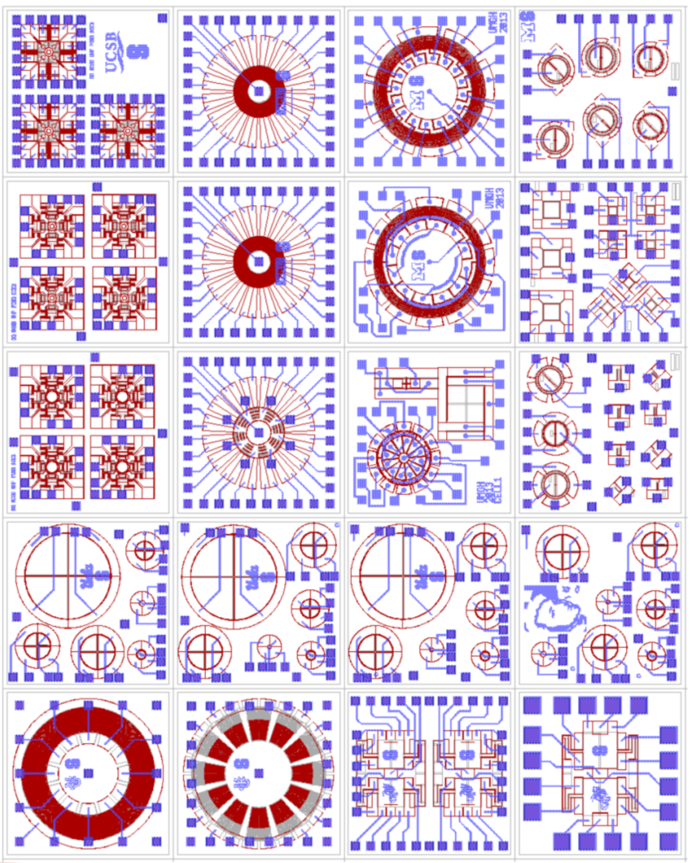
Encapsulation Process – High Yield

Our runs include a huge variety of devices – opportunity to determine materials properties.



Parameter extraction carried out through extensive "Data Mining" F(T) results from our "library" of devices.

C_{11}, C_{12}, C_{44} as a function of temperature and doping extracted.



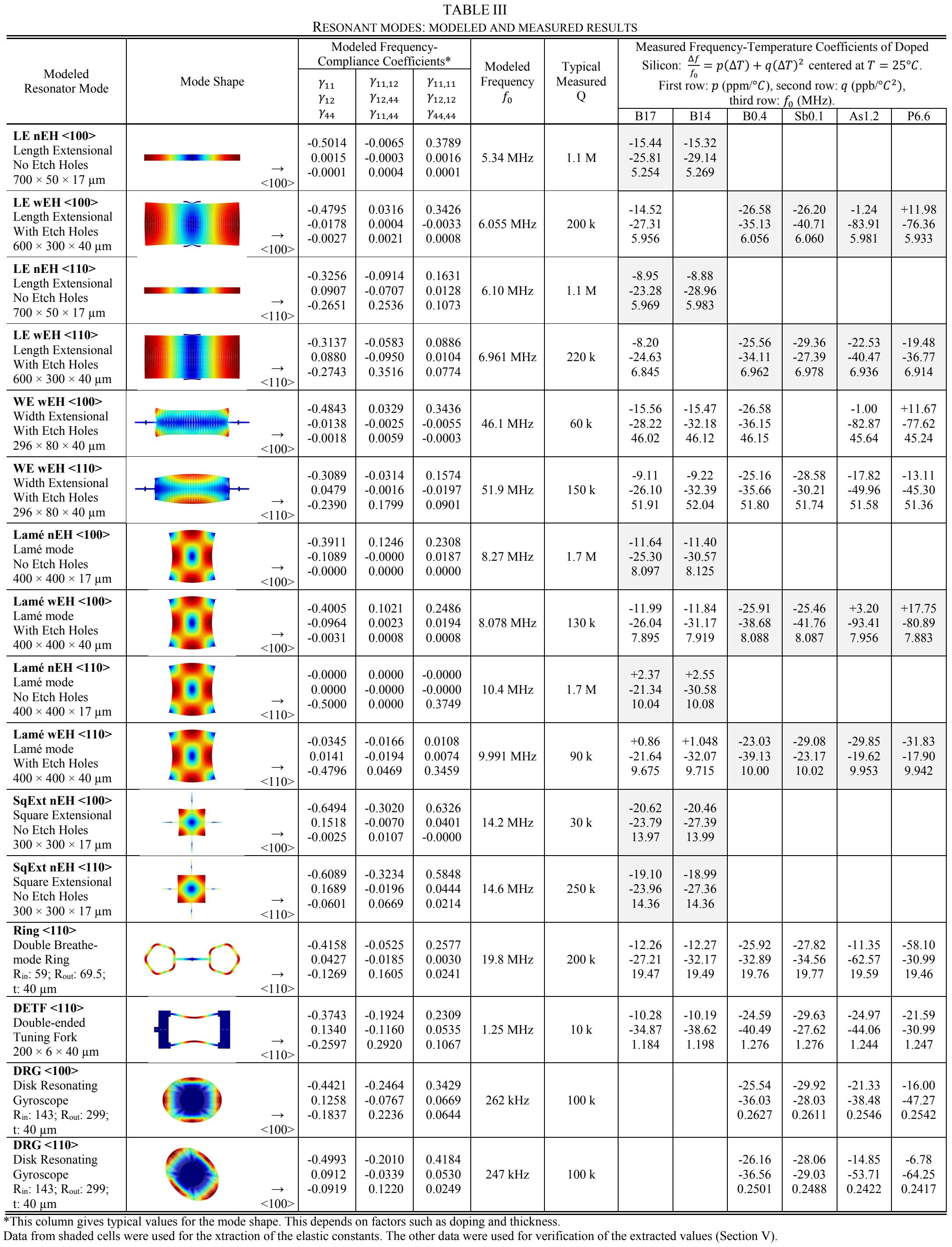


TABLE III

RESONANT MODES: MODELED AND MEASURED RESULTS

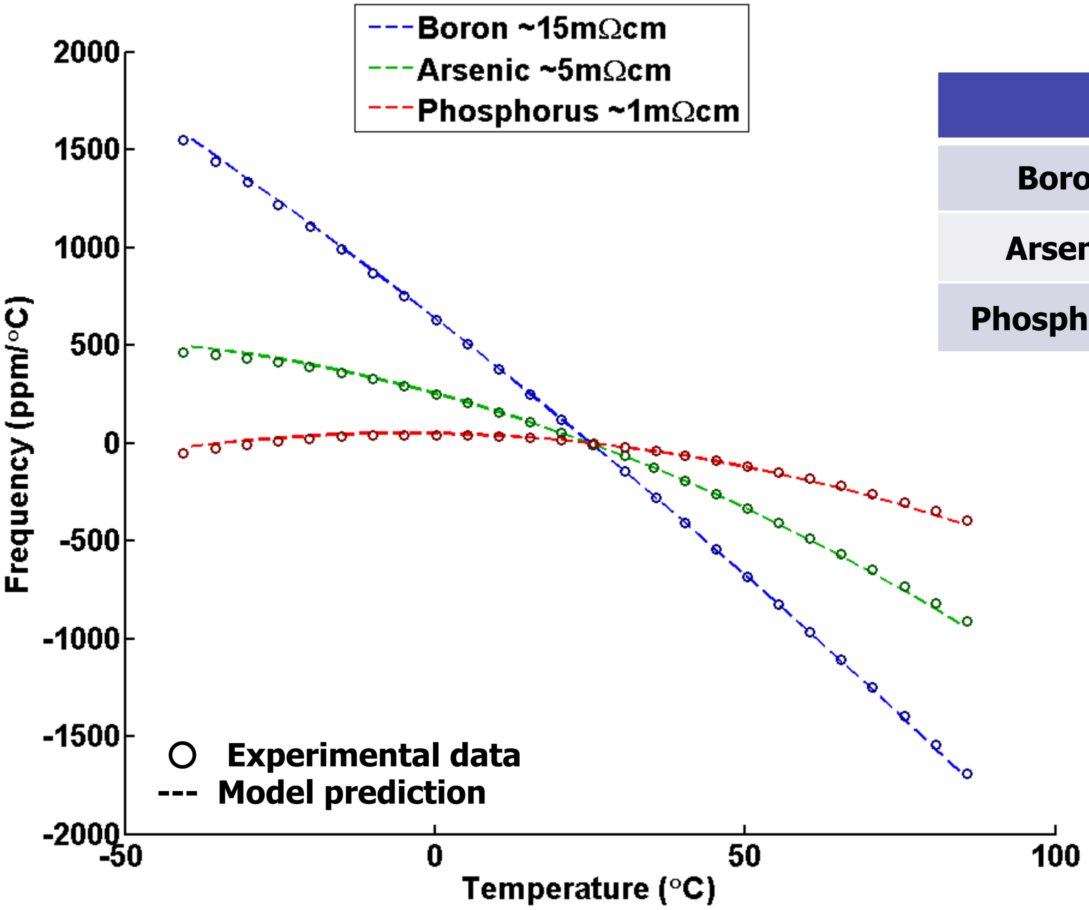
Modeled Resonator Mode	Mode Shape	Modeled Frequency-Compliance Coefficients*			Modeled Frequency f_0	Typical Measured Q	Measured Frequency-Temperature Coefficients of Doped Silicon: $\frac{\Delta f}{f_0} = p(\Delta T) + q(\Delta T)^2$ centered at $T = 25°C$. First row: p (ppm/°C), second row: q (ppb/°C^2), third row: f_0 (MHz).					
		γ_{11} γ_{12} γ_{44}	$\gamma_{11,12}$ $\gamma_{12,44}$ $\gamma_{11,44}$	$\gamma_{11,11}$ $\gamma_{12,12}$ $\gamma_{44,44}$			B17	B14	B0.4	Sb0.1	As1.2	P6.6
LE nEH <100> Length Extensional No Etch Holes 700 × 50 × 17 µm	→ <100>	-0.5014 0.0015 -0.0001	-0.0065 -0.0003 0.0004	0.3789 0.0016 0.0001	5.34 MHz	1.1 M	-15.44 -25.81 5.254	-15.32 -29.14 5.269				
LE wEH <100> Length Extensional With Etch Holes 600 × 300 × 40 µm	→ <100>	-0.4795 -0.0178 -0.0027	0.0316 0.0004 0.0021	0.3426 -0.0033 0.0008	6.055 MHz	200 k	-14.52 -27.31 5.956		-26.58 -35.13 6.056	-26.20 -40.71 6.060	-1.24 -83.91 5.981	+11.98 -76.36 5.933
LE nEH <110> Length Extensional No Etch Holes 700 × 50 × 17 µm	→ <110>	-0.3256 0.0907 -0.2651	-0.0914 -0.0707 0.2536	0.1631 0.0128 0.1073	6.10 MHz	1.1 M	-8.95 -23.28 5.969	-8.88 -28.96 5.983				
LE wEH <110> Length Extensional With Etch Holes 600 × 300 × 40 µm	→ <110>	-0.3137 0.0880 -0.2743	-0.0583 -0.0950 0.3516	0.0886 0.0104 0.0774	6.961 MHz	220 k	-8.20 -24.63 6.845		-25.56 -34.11 6.962	-29.36 -27.39 6.978	-22.53 -40.47 6.936	-19.48 -36.77 6.914
WE wEH <100> Width Extensional With Etch Holes 296 × 80 × 40 µm	→ <100>	-0.4843 -0.0138 -0.0018	0.0329 -0.0025 0.0059	0.3436 -0.0055 -0.0003	46.1 MHz	60 k	-15.56 -28.22 46.02	-15.47 -32.18 46.12	-26.58 -36.15 46.15		-1.00 -82.87 45.64	+11.67 -77.62 45.24
WE wEH <110> Width Extensional With Etch Holes 296 × 80 × 40 µm	→ <110>	-0.3089 0.0479 -0.2390	-0.0314 -0.0016 0.1799	0.1574 -0.0197 0.0901	51.9 MHz	150 k	-9.11 -26.10 51.91	-9.22 -32.39 52.04	-25.16 -35.66 51.80	-28.58 -30.21 51.74	-17.82 -49.96 51.58	-13.11 -45.30 51.36
Lamé nEH <100> Lamé mode No Etch Holes 400 × 400 × 17 µm	→ <100>	-0.3911 -0.1089 -0.0000	0.1246 -0.0000 0.0000	0.2308 0.0187 0.0000	8.27 MHz	1.7 M	-11.64 -25.30 8.097	-11.40 -30.57 8.125				
Lamé wEH <100> Lamé mode With Etch Holes 400 × 400 × 40 µm	→ <100>	-0.4005 -0.0964 -0.0031	0.1021 0.0023 0.0008	0.2486 0.0194 0.0008	8.078 MHz	130 k	-11.99 -26.04 7.895	-11.84 -31.17 7.919	-25.91 -38.68 8.088	-25.46 -41.76 8.087	+3.20 -93.41 7.956	+17.75 -80.89 7.883
Lamé nEH <110> Lamé mode No Etch Holes 400 × 400 × 17 µm	→ <110>	-0.0000 0.0000 -0.5000	0.0000 -0.0000 0.0000	-0.0000 -0.0000 0.3749	10.4 MHz	1.7 M	+2.37 -21.34 10.04	+2.55 -30.58 10.08				
Lamé wEH <110> Lamé mode With Etch Holes 400 × 400 × 40 µm	→ <110>	-0.0345 0.0141 -0.4796	-0.0166 -0.0194 0.0469	0.0108 0.0074 0.3459	9.991 MHz	90 k	+0.86 -21.64 9.675	+1.048 -32.07 9.715	-23.03 -39.13 10.00	-29.08 -23.17 10.02	-29.85 -19.62 9.953	-31.83 -17.90 9.942
SqExt nEH <100> Square Extensional No Etch Holes 300 × 300 × 17 µm	→ <100>	-0.6494 0.1518 -0.0025	-0.3020 -0.0070 0.0107	0.6326 0.0401 -0.0000	14.2 MHz	30 k	-20.62 -23.79 13.97	-20.46 -27.39 13.99				
SqExt nEH <110> Square Extensional No Etch Holes 300 × 300 × 17 µm	→ <110>	-0.6089 0.1689 -0.0601	-0.3234 -0.0196 0.0669	0.5848 0.0444 0.0214	14.6 MHz	250 k	-19.10 -23.96 14.36	-18.99 -27.36 14.36				
Ring <110> Double Breathe-mode Ring R_{in}: 59; R_{out}: 69.5; t: 40 µm	→ <110>	-0.4158 0.0427 -0.1269	-0.0525 -0.0185 0.1605	0.2577 0.0030 0.0241	19.8 MHz	200 k	-12.26 -27.21 19.47	-12.27 -32.17 19.49	-25.92 -32.89 19.76	-27.82 -34.56 19.77	-11.35 -62.57 19.59	-58.10 -30.99 19.46
DETF <110> Double-ended Tuning Fork 200 × 6 × 40 µm	→ <110>	-0.3743 0.1340 -0.2597	-0.1924 -0.1160 0.2920	0.2309 0.0535 0.1067	1.25 MHz	10 k	-10.28 -34.87 1.184	-10.19 -38.62 1.198	-24.59 -40.49 1.276	-29.63 -27.62 1.276	-24.97 -44.06 1.244	-21.59 -30.99 1.247
DRG <100> Disk Resonating Gyroscope R_{in}: 143; R_{out}: 299; t: 40 µm	→ <100>	-0.4421 0.1258 -0.1837	-0.2464 -0.0767 0.2236	0.3429 0.0669 0.0644	262 kHz	100 k			-25.54 -36.03 0.2627	-29.92 -28.03 0.2611	-21.33 -38.48 0.2546	-16.00 -47.27 0.2542
DRG <110> Disk Resonating Gyroscope R_{in}: 143; R_{out}: 299; t: 40 µm	→ <100>	-0.4993 0.0912 -0.0919	-0.2010 -0.0339 0.1220	0.4184 0.0530 0.0249	247 kHz	100 k			-26.16 -36.56 0.2501	-28.06 -29.03 0.2488	-14.85 -53.71 0.2422	-6.78 -64.25 0.2417

*This column gives typical values for the mode shape. This depends on factors such as doping and thickness.

Data from shaded cells were used for the xtraction of the elastic constants. The other data were used for verification of the extracted values (Section V).

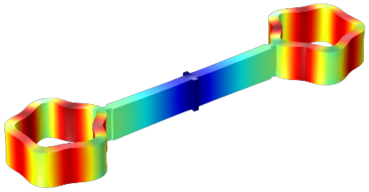
Status: Temperature Compensation

- **Model Verification: Dual Breathe-mode Ring Resonator**



Frequency at 25°C (MHz)

	Measured	Predicted
Boron	19.764	19.697
Arsenic	19.586	19.542
Phosphorus	19.459	19.432



Status: Temperature Compensation

Temperature Dependence of the Elastic Constants of Doped Silicon

Eldwin J. Ng, Vu A. Hong, Yushi Yang, Chae Hyuck Ahn, Camille L.M. Everhart, Thomas W. Kenny

DOPING DEPENDENCE OF THE ELASTIC CONSTANTS AND THEIR TEMPERATURE DEPENDENCES

Doping Type and Concentration (cm^{-3})	c_{11} (GPa) s_{11} (10^{-12} Pa^{-1})	c_{12} (GPa) s_{12} (10^{-12} Pa^{-1})	c_{44} (GPa) s_{44} (10^{-12} Pa^{-1})	$Tc_{11}^{(1)}$ $Ts_{11}^{(1)}$ (ppm/°C)	$Tc_{12}^{(1)}$ $Ts_{12}^{(1)}$ (ppm/°C)	$Tc_{44}^{(1)}$ $Ts_{44}^{(1)}$ (ppm/°C)	$Tc_{11}^{(2)}$ $Ts_{11}^{(2)}$ (ppb/°C^2)	$Tc_{12}^{(2)}$ $Ts_{12}^{(2)}$ (ppb/°C^2)	$Tc_{44}^{(2)}$ $Ts_{44}^{(2)}$ (ppb/°C^2)
Boron 1.7e20	163.2 7.835	63.5 -2.195	75.3 13.28	-56.7 33.7	-104.8 -1.0	1.9 -1.9	-54 60	-44 62	-52 52
Boron 1.4e20	163.3 7.846	63.8 -2.205	75.5 13.25	-56.9 33.4	-105.5 -1.5	2.2 -2.2	-57 68	-37 78	-71 71
Boron 4.1e18	165.7 7.719	64.5 -2.163	79.2 12.63	-63.4 56.6	-77.5 46.4	-48.3 48.3	-50 80	7 120	-88 90
Antimony 1.3e18	165.6 7.720	64.4 -2.162	79.3 12.61	-65.5 56.1	-85.1 42.0	-60.9 60.9	-68 90	-28 117	-53 56
Arsenic 1.2e19	164.2 7.890	65.6 -2.252	78.6 12.72	-46.6 7.0	-124.6 -48.7	-63.1 63.1	-105 176	32 270	-45 49
Phosphorus 6.6e19	164.0 7.973	66.7 -2.305	78.2 12.78	-34.2 -18.9	-135.2 -90.7	-67.8 67.8	-103 159	-1 228	-40 45

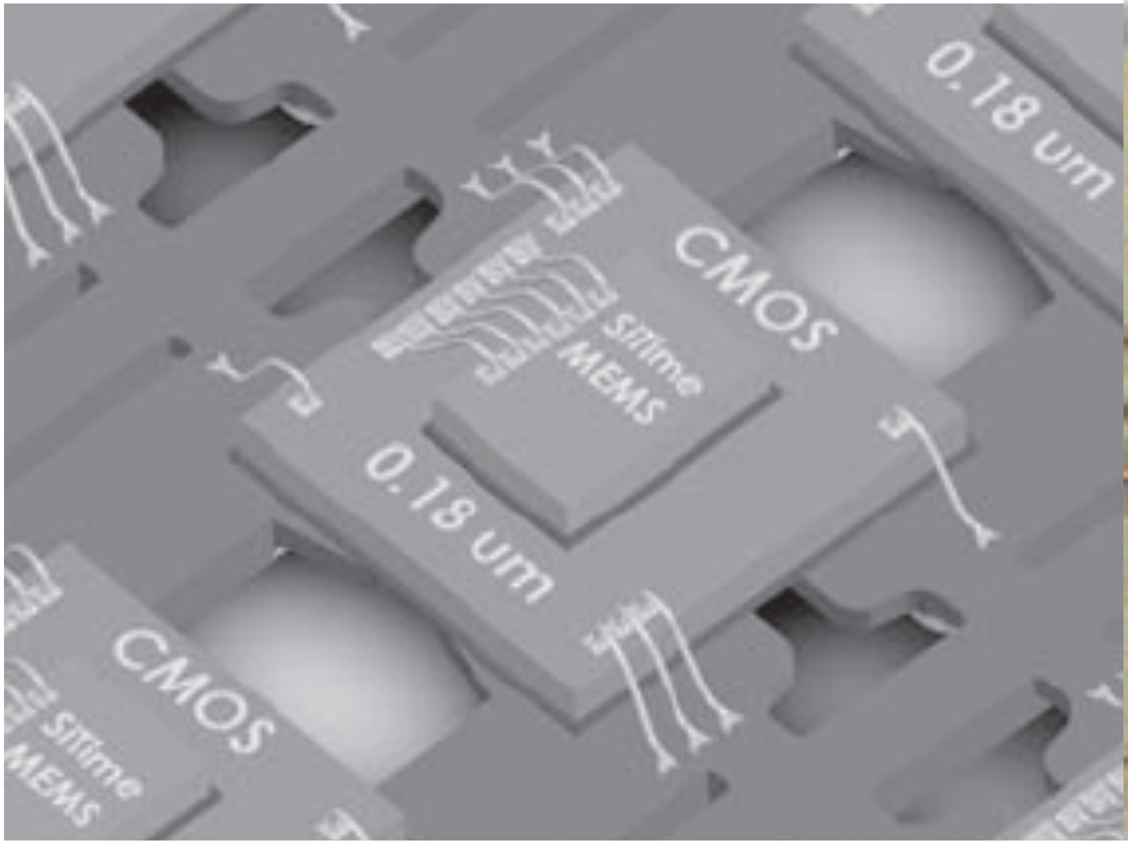
JMEMS '14 in press
Available at JMEMS Website –
Open Access

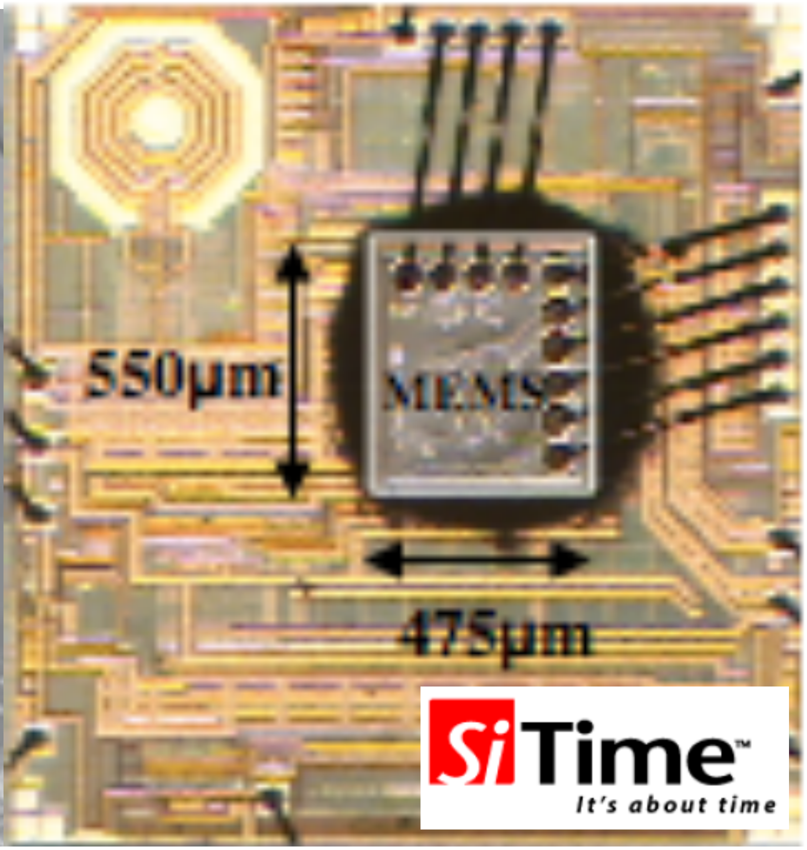
- **Data and Paper can be downloaded from:**

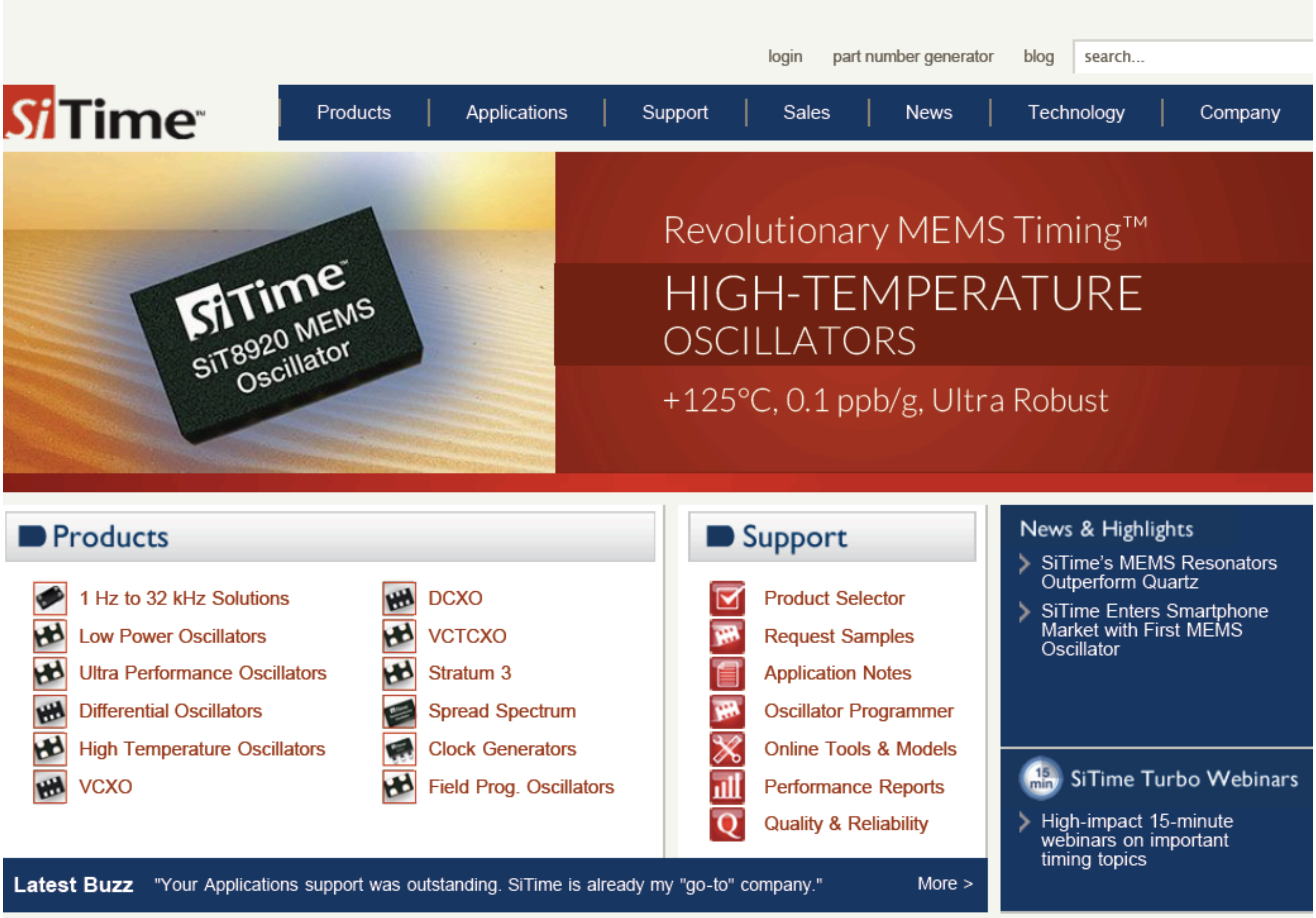
http://micromachine.stanford.edu/projects/doping/

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 for Agile and Diverse Product Portfolio
  - Compatible with Temperature Compensation Schemes
- All helpful for Commercialization!







Revolutionary MEMS Timing™

HIGH-TEMPERATURE OSCILLATORS

+125°C, 0.1 ppb/g, Ultra Robust

Products

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- Low Power Oscillators
- Ultra Performance Oscillators
- Differential Oscillators
- High Temperature Oscillators
- VCXO
- DCXO
- VCTCXO
- Stratum 3
- Spread Spectrum
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- Request Samples
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- Oscillator Programmer
- Online Tools & Models
- Performance Reports
- Quality & Reliability

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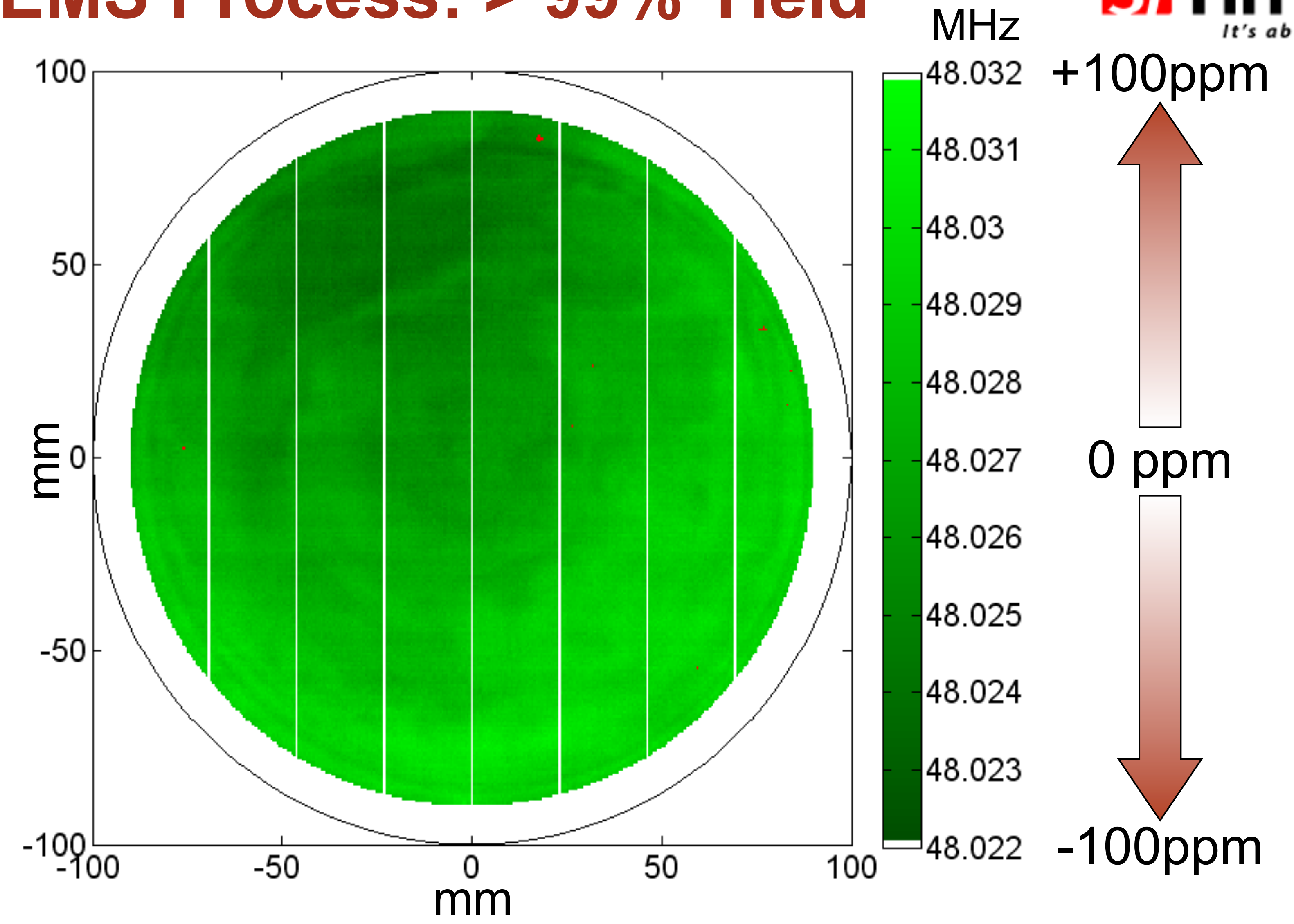
- SiTime's MEMS Resonators Outperform Quartz
- SiTime Enters Smartphone Market with First MEMS Oscillator

SiTime Turbo Webinars

- High-impact 15-minute webinars on important timing topics

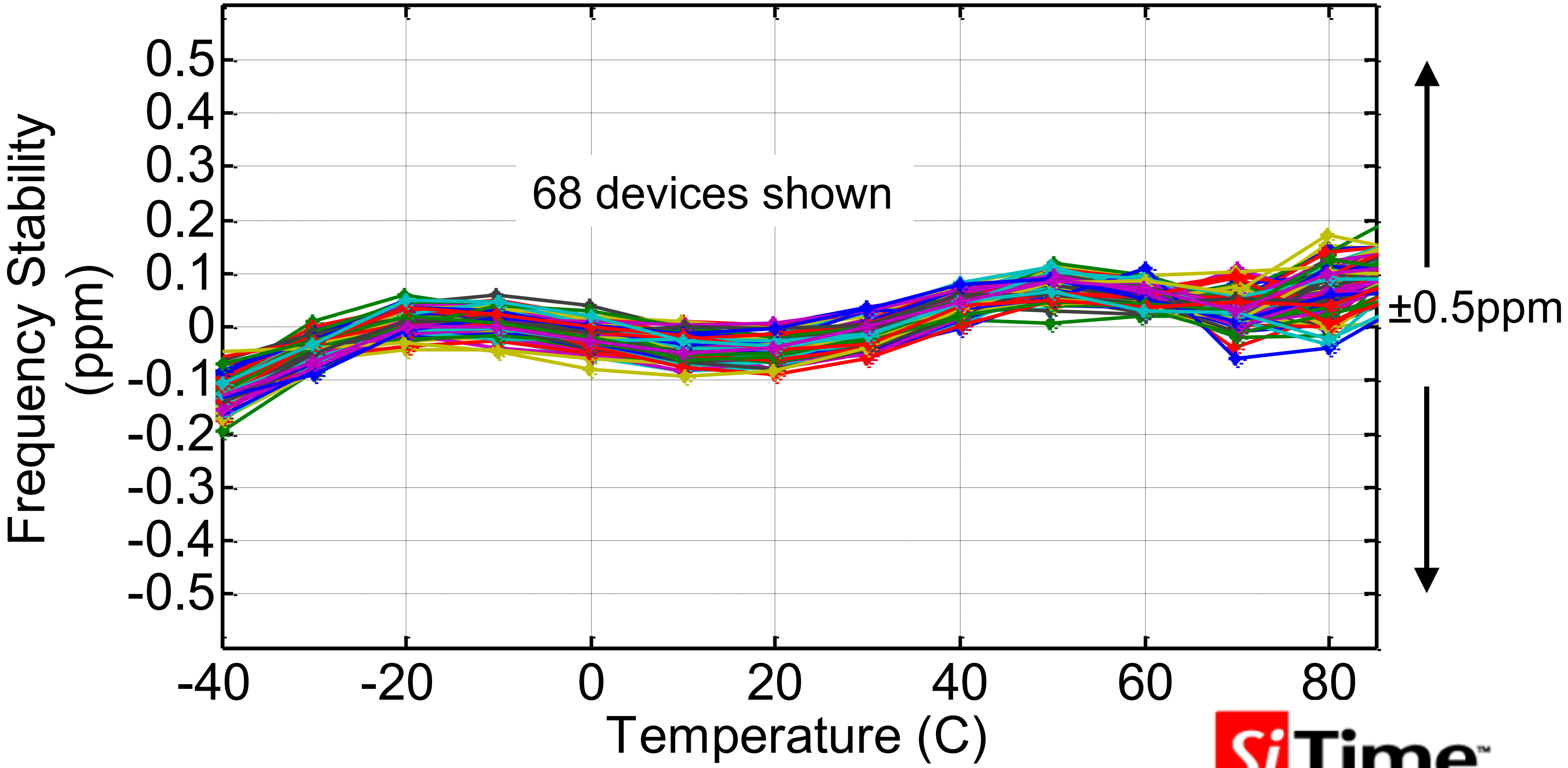
Latest Buzz "Your Applications support was outstanding. SiTime is already my "go-to" company." More >

MEMS Process: > 99% Yield



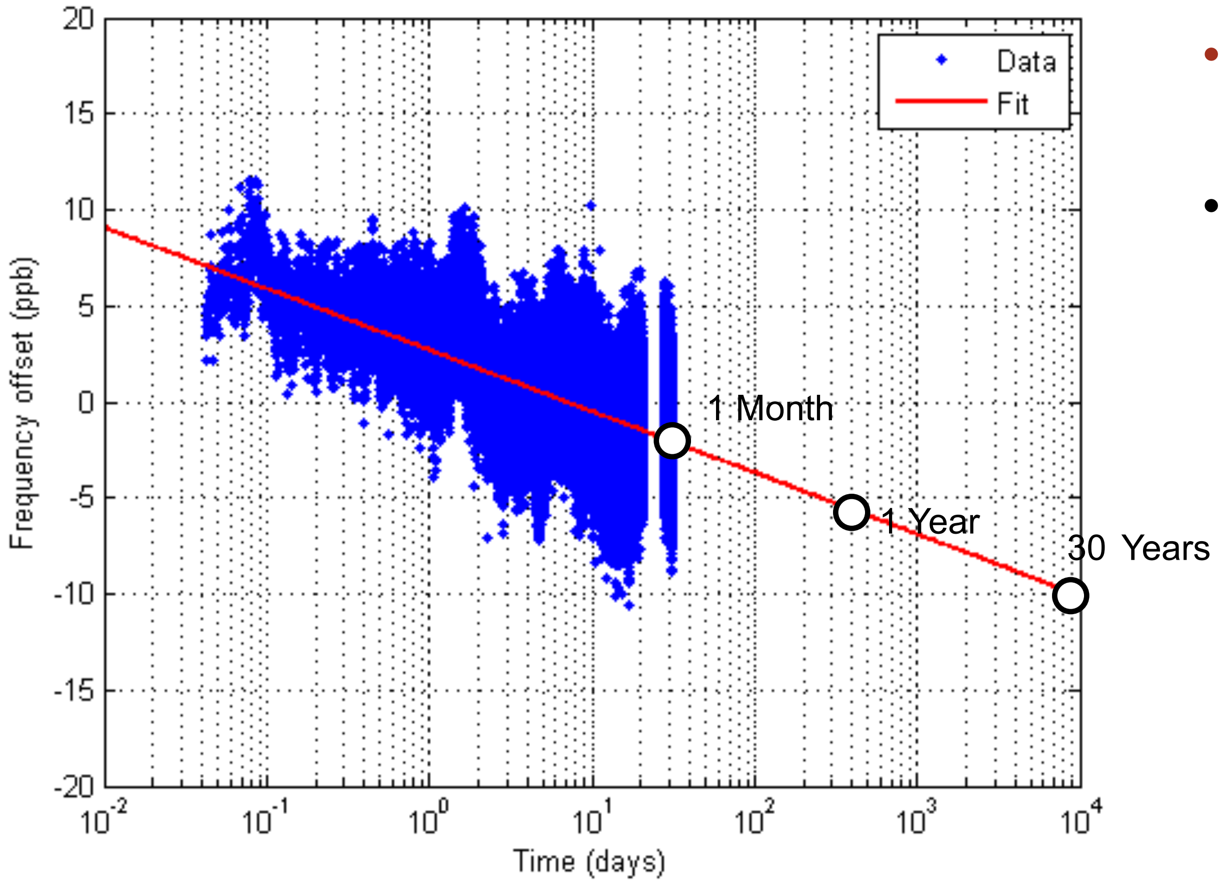
200mm thinned wafer with ~70,000 resonators

Sub-PPM Stability



Uses Compensated Silicon and Calibration for Stability

Aging Projections for Current SiTime Products



- **Better** than Quartz
- Far better than any other MEMS made in any other technology

SiTime™ It's about time

SiTime Status, 10 years after launch

- >250M 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.
- Advantages over Quartz in Cost, Size, Performance, Power
- **ALL Enabled by PACKAGING!**

SiTime Status, 10 years after launch –

Why did it take SOOOO Long?

- We had MEMS, needed CMOS
    - Mixed signal, low power, PLL, temp sensor, NVM,…

- We had devices, needed products
    - Complete set of specifications

- By the time we had products, we needed customers
    - Why would anyone take a risk on a ~$0.30 part?

- Only recently have we had compelling products.
    - Finally, serious customers with serious interest!

SiT1532 Preliminary

Smallest Footprint (1.2mm^2), Ultra-Low Power 32.768 kHz Oscillator in CSP

SiTime

The Smart Timing Choice™

Features

- Smallest footprint in chip-scale (CSP): 1.5 x 0.8 mm
- Ultra-low power: <1μA
- Supports coin-cell or super-cap battery backup voltages
- Vdd supply range: 1.5V to 3.63V over -40°C to +85°C
- Oscillator output eliminates external load caps
- NanoDrive™ programmable output swing for lowest power
- Internal filtering eliminates external Vdd bypass cap
- Fixed 32.768 kHz
- <20 PPM initial stability
- <100 PPM stability over -40°C to +85°C
- Pb-free, RoHS and REACH compliant

Applications

- Mobile Phones
- Tablets
- Health and Wellness Monitors
- Fitness Watches
- Sport Video Cams
- Wireless Keypads
- Ultra-Small Notebook PC
- Pulse-per-Second (pps) Timekeeping
- RTC Reference Clock
- Battery Management Timekeeping

EXPRESS SAMPLES

GREEN SOLUTIONS

QUARTZ FREE

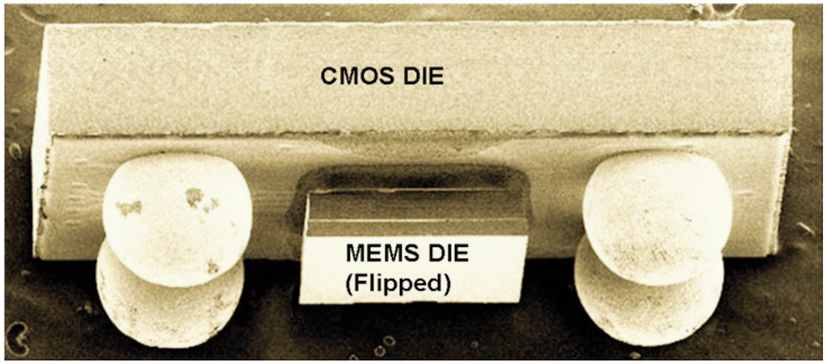


Figure 12.9.7: Micrograph of MEMS and CMOS dies and final CSP package.

Packaging :

Wafer-scale encapsulation
Enables CSP product

- Largest acquisition of a venture-backed semiconductor company in 2014
- MegaChips becomes a leader in MEMS with SiTime's 80% share in MEMS timing
- MegaChips' revenue of $600M provides scale and growth for MEMS

SUNNYVALE, Calif. – October 28, 2014 – SiTime Corporation, a MEMS and analog semiconductor company, today announced that it has signed a definitive agreement under which MegaChips Corporation (Tokyo Stock Exchange: 6875), a top 25 fabless semiconductor company based in Japan, will acquire SiTime for $200 million in cash. This transaction combines two complementary fabless semiconductor leaders that provide solutions for the growing Wearables, Mobile and Internet of Things markets.

"SiTime's founders, Markus Lutz and Dr. Aaron Partridge, started the company with a vision of developing game-changing MEMS and analog technology to revolutionize the $5 billion timing industry," said Rajesh Vashist, CEO of SiTime. "Through innovation, passion and focus, we've successfully delivered on this vision. Today, SiTime is the overwhelming leader – we have 1000 customers, 250 million units shipped, major design wins in all electronics segments, and a roadmap that extends SiTime's MEMS technology to all timing markets."

Some Thoughts after a Good Outcome

- Replacement Products are HARD to Insert into Market
    - Customers are Entrenched
    - Existing Technology is not Static

- Fundraising is a Continuous Process
    - You don’t want too much money
    - You can’t have enough money
    - “Smart Money” can REALLY help
    - Serious Venture Capitalists can be Patient

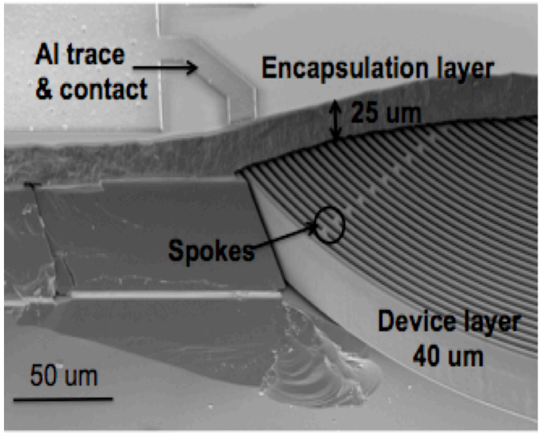
- Lots of things can go Wrong
    - Global Economic Downturns
    - Floods in Thailand, Earthquakes in Japan
    - Take the Good Exit when it Comes!

So, What is the Kenny Group Doing?

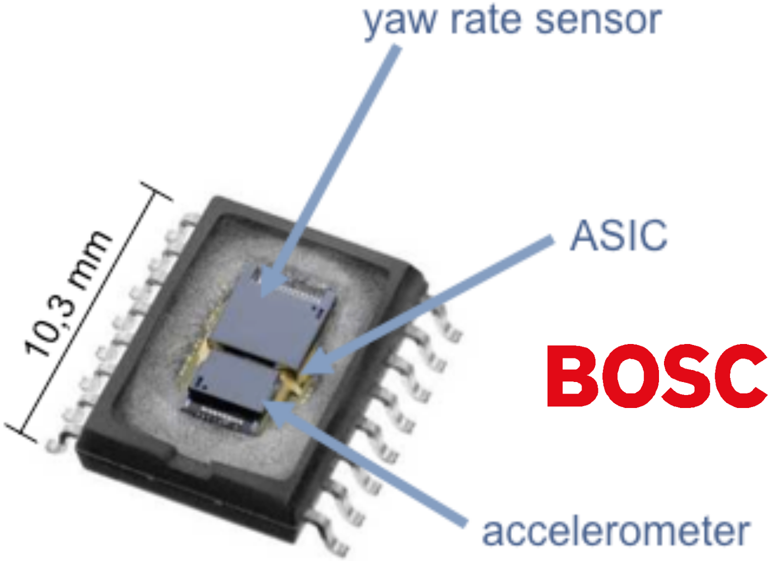
We have :

Wafer-Scale Film Encapsulation

- Ultra-clean, high-quality process
- Demonstrated Stability, Yield, Reliability
- Full production at SiTime
- Minimum Volume Package for MEMS



Can we build single-chip “ComboSensors”?



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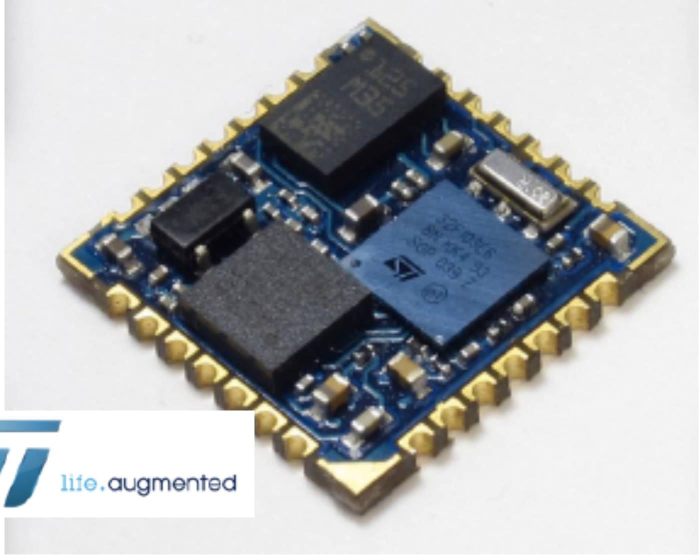

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Encapsulated Pressure Sensor + Thermometer

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

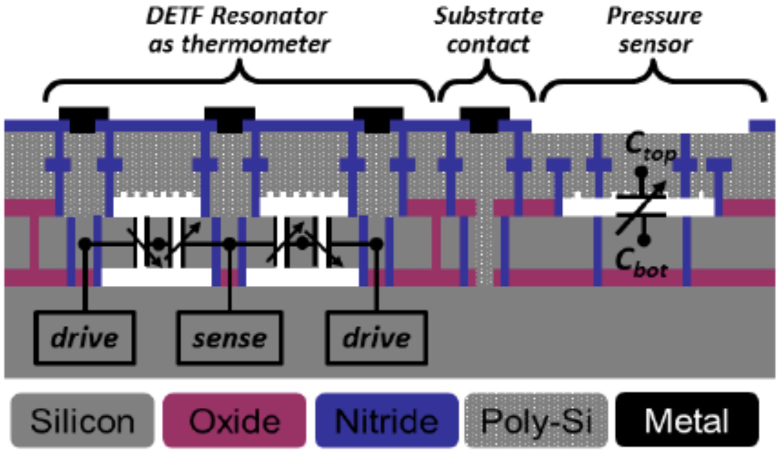

Figure 1: A cross-sectional view of the cofabricated DETF resonant thermometer and capacitive pressure sensor.

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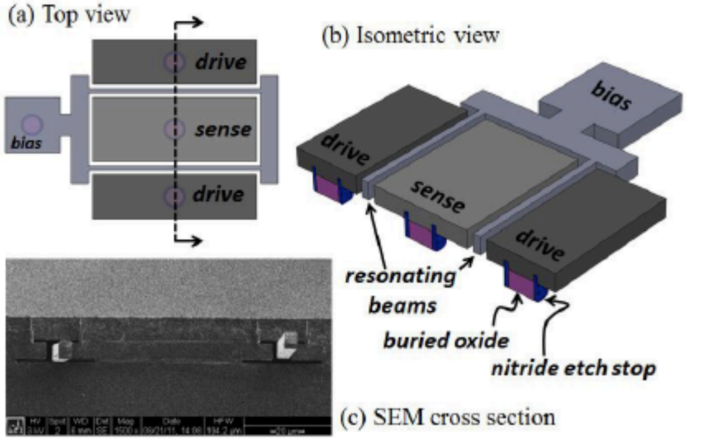


Figure 2: Schematic and cross-sectional SEM images of a DETF resonant thermometer.

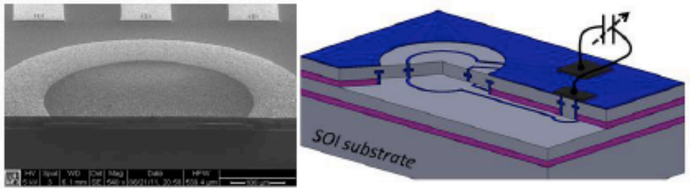
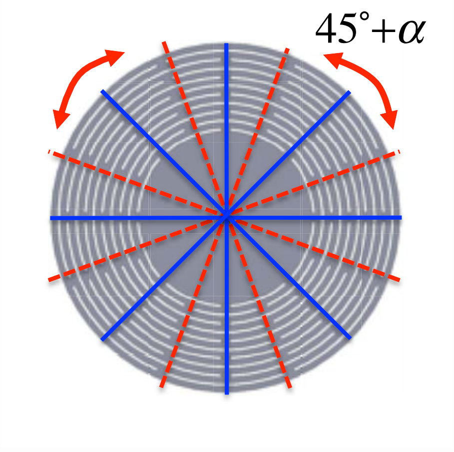


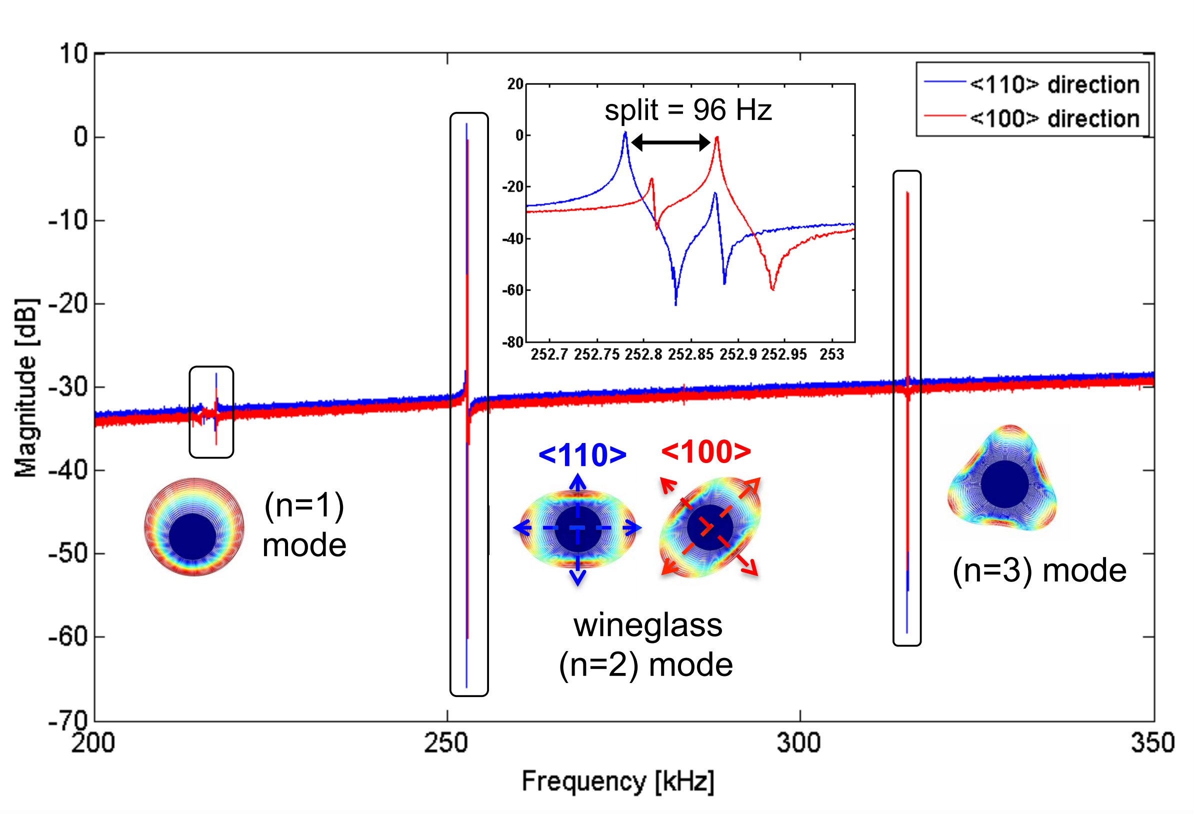
Figure 3: Structure of the capacitive pressure sensor.

Mode-Matching of Wineglass Mode Disk Resonator Gyroscope in (100) Single Crystal Silicon

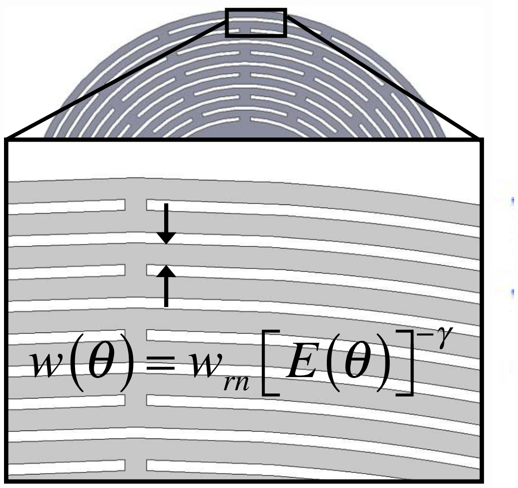
Chae Hyuck Ahn, Eldwin J. Ng, Vu A. Hong, Yushi Yang, Brian J. Lee, Ian Flader, and Thomas W. Kenny



(a)



(b)

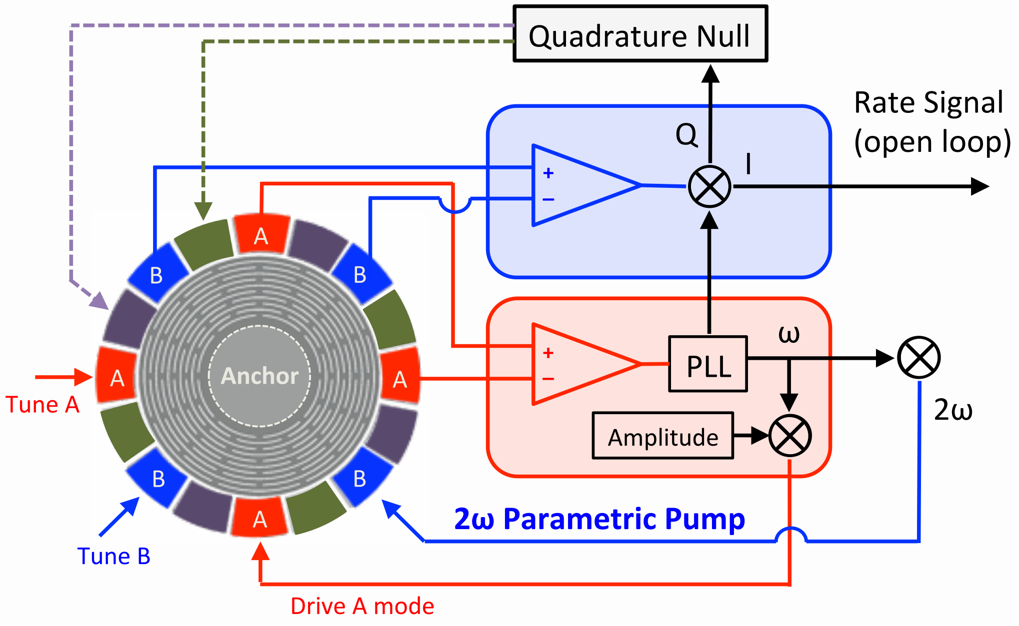


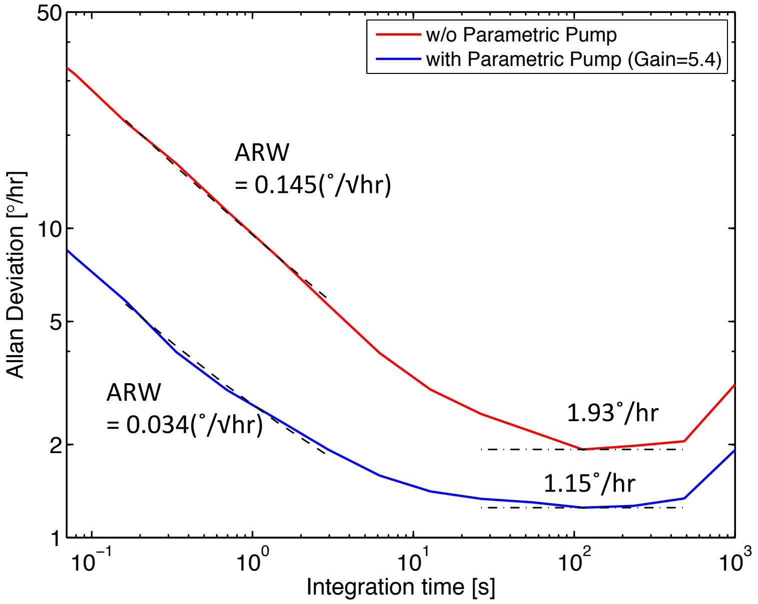
(c)

JMEMS 2014

Encapsulated High Frequency (235kHz), High-Q (100k) Disk Resonator Gyroscope (DRG) with Electrostatic Parametric Pump [a)]

C.H. Ahn[1)], S. Nitzan[2)], E.J. Ng[1)], V.A. Hong[1)], Y.Yang[1)], T. Kimbrell[1)], D.A. Horsley[2)], and T.W. Kenny[1)]





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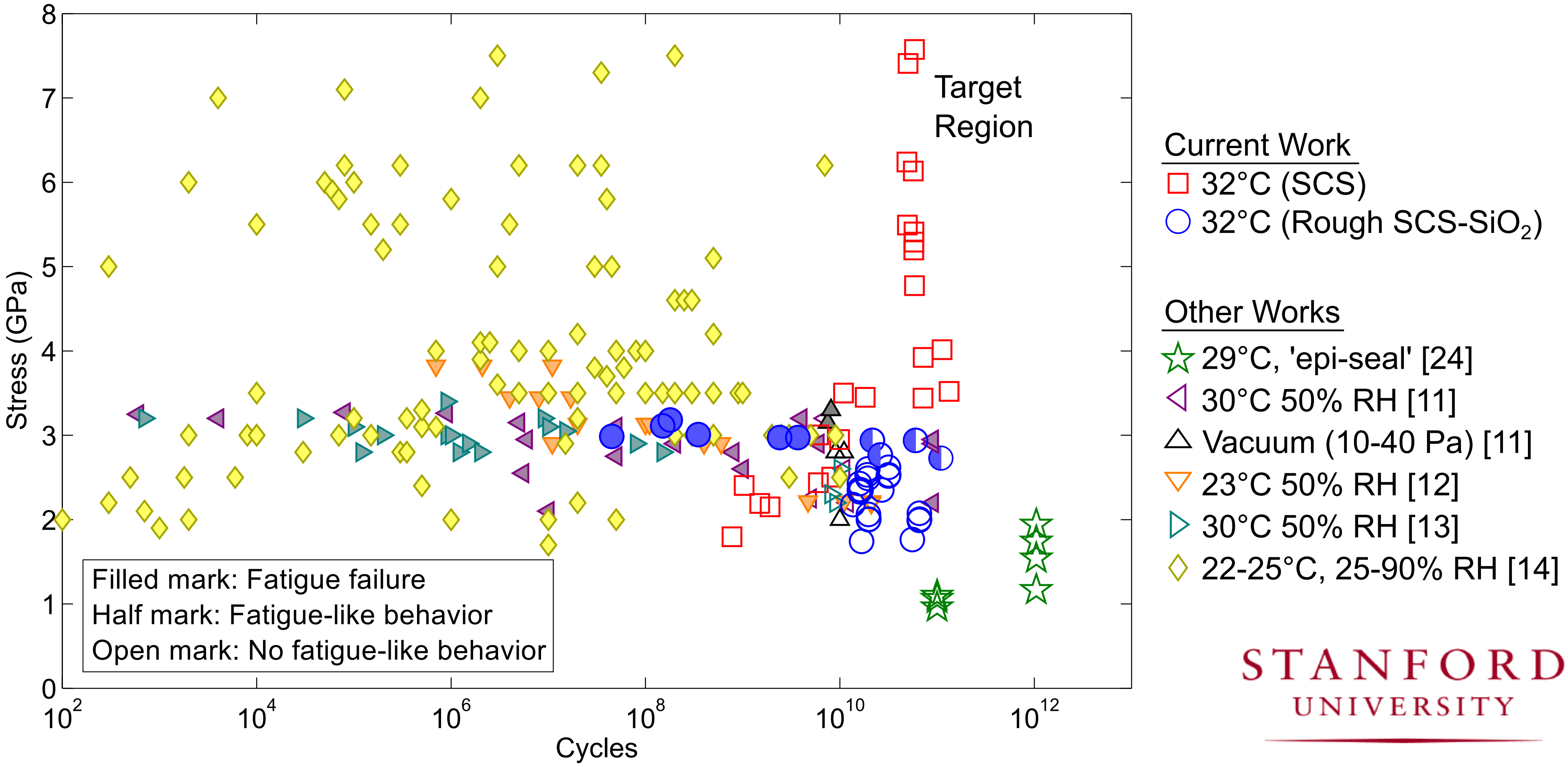
Appl. Phys. Lett. **105**, 243504 (2014)

Fatigue Experiments on Single Crystal Silicon in an Oxygen-Free Environment

Vu A. Hong, Shingo Yoneoka, Matthew W. Messana, Andrew B. Graham, James C. Salvia,
Todd T. Branchflower, Eldwin J. Ng, and Thomas W. Kenny



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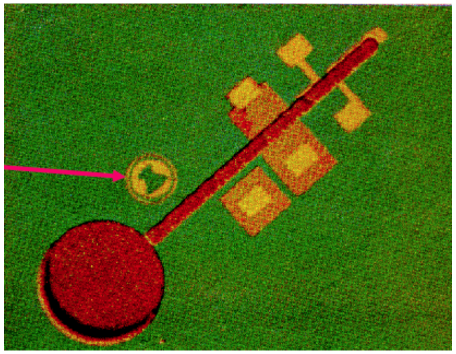
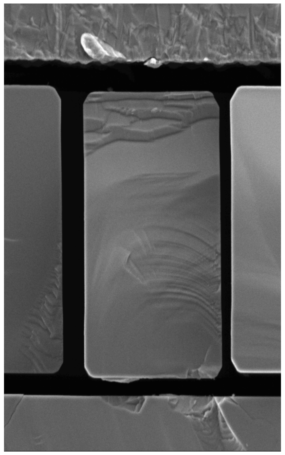
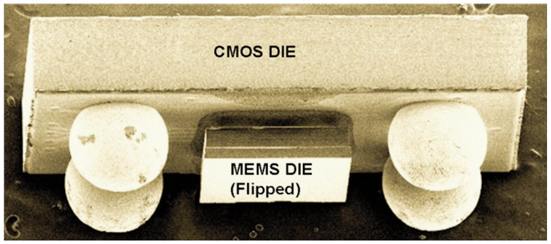
The LONG Path from MEMS Resonators to Timing Products

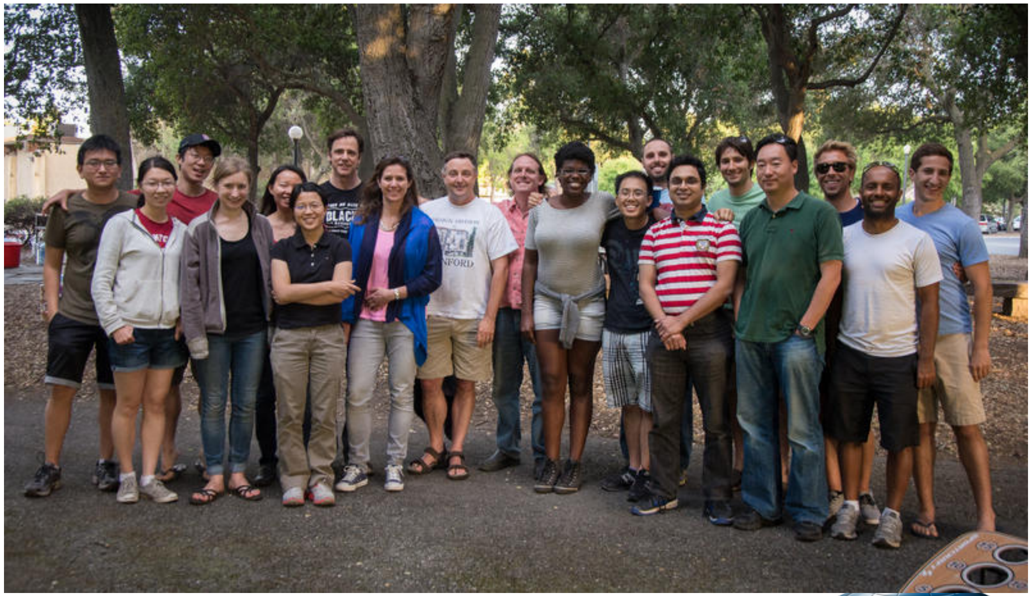






Based on PhD work of :

Eldwin Ng, Yushi Yang, Vu Hong, Chae Ahn, David Heinz, Ian Flader, Camille Everhart, Yunhan Chen, Shirin Gaffari, Chia-Fang Chiang, Bongsang Kim, Saurabh Chandorkar, Gaurav Bahl, Renata Melamud, Rob Candler, Woo-Tae Park, Matt Hopcroft, Jim Salvia, Shingo Yoneoka, Andrew Graham, Matt Messana, HyungKyu Lee, Shasha Wang, Aaron Partridge



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