

THE LONG PATH FROM MEMS RESONATORS TO TIMING PRODUCTS

E. Ng¹, Y. Yang¹, V.A. Hong¹, C.H. Ahn¹, D.B. Heinz¹, I. Flader¹, Y. Chen¹, C.L.M. Everhart¹, B. Kim², R. Melamud², R.N. Candler², M.A. Hopcroft², J.C. Salvia², S. Yoneoka², A.B. Graham², M. Agarwal², M.W. Messana², K.L. Chen², H.K. Lee², S. Wang², G. Bahl², V. Qu², C.F. Chiang², and T.W. Kenny¹
A. Partridge³, M. Lutz³, G. Yama⁴ and G.J. O'Brien⁴

¹Department of Mech.Eng., Stanford, ²PhD Alumni of Stanford, ³SiTime Inc, Mt. View, CA

⁴Robert Bosch Research and Technology Center, Palo Alto, CA

ABSTRACT

Research on MEMS Resonators began over 50 years ago. In just the last 10 years, there has been a series of important technological developments, and (finally!) success at commercialization. The presentation will highlight some key milestones along this path, describe some of the critical technology steps, and outline some of the important non-technological events within SiTime – all of these factors contributed to the successful outcome.

RESONATOR HISTORY

The history of MEMS and MEMS Resonators begins with the Resonant Gate Transistor [1], developed by Nathanson over 50 years ago. This is arguably the first device with all of the essential elements of MEMS. Nathanson described it as a time reference; and many challenging issues associated with fatigue, temperature coefficients, and reliability were already noted.

MEMS resonators were discussed as an important application of Silicon MEMS [2] by Petersen more than 30 years ago. In his paper, the challenge for success in MEMS Resonators is identified as (1) “...offering functions that cannot easily be duplicated by conventional...” approaches, (2) “...solve the inherent problems of mechanical reliability and reproducibility...”, and (3) “...are fabricated by techniques totally compatible with standard IC processing...”.

The first big step towards a manufacturable resonator technology was demonstrated 25 years ago by Tang and Howe [3], in the form of the surface micromachined comb drive resonator. While there were many challenges remaining to produce stable time references, the Tang and Howe comb drive became the basis for accelerometers and gyroscopes developed through the 1990s and is represented in all MEMS for consumer electronics today. Shortly thereafter, DeRooy demonstrated integration of capacitive, thermal, and piezoresistive resonators [4] and Cabuz and Esashi demonstrated resonant IR Sensors [5]. The field of Resonant MEMS was established!

To solve problems with stability, Esashi began focusing on packaging of MEMS resonators including getters [6], along with Guckel, Lee, and Chun [7-9]. In all of this work, researchers were focused on low pressure, hermeticity, and stability. In parallel with these Si-based activities, Ruby demonstrated the first FBARs [10]; this technology has led to the manufacture and sale of billions of MEMS resonators for RF filter applications.

Even with all this effort, success at meeting the goals outlined by Petersen was elusive. Packaged MEMS resonators were not stable enough for timing applications, and quartz technology was more than sufficient to satisfy

market needs. To meet some particularly challenging goals for the US Department of Defense, Nguyen established a DARPA program on MEMS packaging [11], which focused on long-term stability and miniaturization.

THE EPI-SEAL PROCESS AND SITIME

In 1999, Robert Bosch opened its Palo Alto Research and Technology Center, adjacent to Stanford. Markus Lutz was among the first technologists at RTC, and came to Stanford seeking collaborators to help demonstrate a wafer-level encapsulation for inertial sensors using standard IC processes; Aaron Partridge was the first of many PhD students to get involved. The first trials utilized the Bosch epi-poly [12] for an initial cap layer and CVD oxide for sealing, and were presented at MEMS '01 [13]. These initial devices built showed insufficiently low pressure and poor long-term stability. To solve this problem, Partridge used epi-poly to form the seal, and it was immediately clear that a significant improvement had been achieved [14].

The main advantages of the epi-poly encapsulation process for MEMS resonators are : (1) Low pressure (near 1 millitorr), (2) Clean residual gas (H₂ only), (3) No outgassing (from 1100C sealing step) and (4) Smooth sidewall surfaces (H₂ annealing [15]).

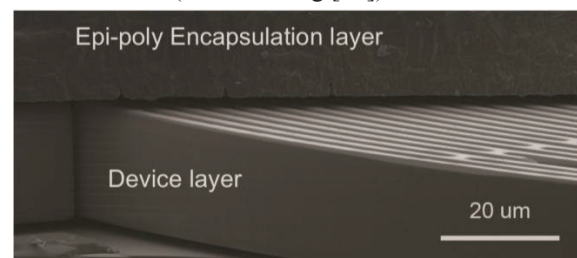


Figure 1 SEM Image of encapsulated MEMS resonator, sealed beneath epi-poly layer in encapsulation process.

With this process, we demonstrated ppm-level stability for extended periods [16], and began to consider formation of a company to commercialize the technology. In 2004, Kurt Petersen joined the team, and by late 2004, there was a technology license from Bosch, \$5M in initial funding, and SiTime was “born” (www.sitime.com).

Around this time, there were other resonator startups, such as Discera (acquired by Micrel in 2013), Silicon Clocks (acquired by SiLabs in 2010), Harmonic Devices (acquired by Qualcomm in 2010), VTI (acquired by Murata in 2012), and Sand9 (independent). Of these, only SiTime has become a large-volume manufacturer of MEMS timing products, responsible for ~90% of MEMS timing products sold to date.

RECENT TECHNOLOGY EVENTS

From the beginning, it was known that the temperature dependence of the modulus of Silicon was too large, at -30 ppm/C, to meet precision timing applications. Early products from SiTime, and other companies, used calibration and digital compensation, which increased the power consumption and phase noise of the products, and made it very hard to compete with the established timing technologies. The most significant recent event in the development of MEMS-based timing was the demonstration of remedies for this problem, based on the use of materials with positive temperature coefficients of modulus (e.g., SiO₂ [16]), or near-degenerate doping [17]. Through these approaches, SiTime built temperature insensitive timing products, and used this breakthrough to greatly reduce power, noise and improve performance. A recent example product delivers a stable clock output with total power consumption less than 1 microWatt [SiTime SiT1532]. All of this led to the recent acquisition of SiTime by Megachips.

In parallel with these activities, Stanford has been active in demonstrating extensions to the basic timing technology. This includes heating the resonator within the encapsulation [18], complete models for the energy dissipation of resonators within this process [19], studies of fatigue [20] and adhesion [21], and suites of accelerometers, pressure sensors, gyroscopes, and other sensors [22] – all within a process similar to the SiTime *episeal* manufacturing process.

REFERENCES

- [1] H.C. Nathanson and R.A. Wickstrom, "A Resonant Gate Silicon Surface Transistor with High-Q Bandpass Properties", *Appl. Phys. Lett.*, 7, 84 (1965).
- [2] K. Petersen, "Silicon as a Mechanical Material", *Proceedings of the IEEE* 70, 420 (1982).
- [3] W.C. Tang, T.C. Nguyen, M.W. Judy and R.T. Howe, "Electrostatic Comb Drive of Lateral Polysilicon Resonators", *S&A* A21-23, 328 (1990).
- [4] C. Linder, M. Gretillat and N.F. de Rooij, "Realization of Different Polysilicon Resonators with Integrated Excitation and Detection Elements", *Microelectronic Engineering* 15, 411 (1991).
- [5] C. Cabuz, S. Shoji, K. Fukatsu, E. Cabuz, K. Minami, and M. Esashi, "Fabrication and Packaging of a Resonant Infrared Sensor Integrated in Silicon", *S&A* A43, 92 (1994).
- [6] H. Henmi, S. Shoji, Y. Shoji, K. Yoshimi and M. Esashi, "Vacuum Packaging for Microsensors by Glass-Silicon Anodic Bonding", *S&A* A43, 243 (1994).
- [7] J.D. Zook, D.W. Burns, H. Guckel, J.J. Sniegowski, R.L. Engelstad and Z. Feng, "Characteristics of Polysilicon Resonant Microbeams", *S&A* A35 (1992).
- [8] L. Lin, K. M. McNair, R. T. Howe, and A. P. Pisano, "Vacuum-Encapsulated Lateral Microresonators," *Proceedings of Transducers 1993*, pp. 270 (1993)
- [9] B. Lee, S. Seok, and K. Chun, "A Study on Wafer Level Vacuum Packaging for MEMS Devices", *J. Micromech. Microeng* 13, 663 (2003).
- [10] R. Ruby and P. Merchant, "Micromachined Thin Film Bulk Acoustic Resonators", *IEEE IFC*, 135 (1994).
- [11] C.T.C. Nguyen, "The Harsh Environment Robust Micromechanical Technology (HERMiT) Program : Success and Some Unfinished Business", 2012 Microwave Symposium Digest, P. 1 (2012), and DARPA BAA 03-11 (2003).
- [12] K. Funk, A. Schlip, M. Offenberger, B. Eisner, and F. Laermer, "Surface Micromachining of Resonant Silicon Structures," *IEEE Transducers* 1995.
- [13] A. Partridge, A. Rice, T.W. Kenny and M. Lutz, "New Thin Film Epitaxial Polysilicon Encapsulation for Piezoresistive Accelerometers", *IEEE MEMS*, P. 54 (2001).
- [14] R.N. Candler, M.A. Hopcroft, B. Kim, W.T. Park, R. Melamud, M. Agarwal, G. Yama, M. Lutz, and T.W. Kenny, "Long-Term and Accelerated Life-Testing of a Novel Single-Wafer Vacuum Encapsulation for MEMS Resonators", *JMEMS* 15, 1446 (2006).
- [15] T. Sato, et.al., "Micro-structure Transformation of Silicon: A Newly Developed Transformation Technology for Patterning Silicon Surfaces using the Surface Migration of Silicon Atoms by Hydrogen Annealing", *Jpn. J. Appl. Phys.* 39, 5033. (2000).
- [16] B.S. Berry and W.C. Pritchett, "Temperature Compensation for Constant Frequency Electromechanical Oscillators", *IBM Tech. Discl. Bull.* 14, (1971), and R. Melamud, et.al., "Temperature Compensated High-Stability Silicon Resonators", *Appl. Phys. Lett* 90, 244107 (2007).
- [17] J.J. Hall, "Electronic Effects in Elastic Constants of N-Type Silicon", *Phys. Rev* 161, 756 (1967), and E.J. Ng, V.A. Hong, Y. Yang, C.H. Ahn, C.L.M. Everhart and T.W. Kenny, "Temperature Dependence of the Elastic Constants of Doped Silicon", *JMEMS* (2015).
- [18] J.C. Salvia, R. Melamud, S.A. Chandorkar, S.F. Lord and T.W. Kenny, "Real-Time Temperature Compensation of MEMS Oscillators Using an Integrated Micro-Oven and a Phase-Locked Loop", *JMEMS* 19, 192 (2010).
- [19] R.Candler, A.Duwel, M.Varghese, S.Chandorkar, M.Hopcroft, W.Park, B. Kim, G. Yama, A. Partridge, M. Lutz and T.W. Kenny, "Impact of Geometry on Thermoelastic Dissipation in Micromechanical Resonant Beams", *JMEMS* 15, 927 (2006).
- [20] V. Hong, et.al., "Fatigue Experiments on Single Crystal Silicon in Oxygen-Free Environment", *JMEMS* (2015).
- [21] D.B. Heinz, et.al., "Stiction Forces and Reduction by Dynamic Contact in Ultra-Clean Encapsulated MEMS Devices", *IEEE MEMS* (2015).
- [22] C.F. Chiang, A.B. Graham, G.J. O'Brien, and T.W. Kenny, "A Single Process for Building Capacitive Pressure Sensors and Timing References with Precise Control of Released Area using lateral Etch Stop", *IEEE MEMS*, P. 519 (2012).

CONTACT

Thomas Kenny, kenny@cdr.stanford.edu