Encapsulated MEMS Resonators – A technology path for MEMS into Frequency Control Applications

B. Kim, R. Melamud, R.A. Candler, M.A Hopcroft, C.M. Jha, S. Chandorkar, and T.W. Kenny
Departments of Mechanical and Electrical Engineering
Stanford University, Stanford, CA 94305

***Abstract*—MEMS resonators have been discussed as replacements for quartz crystals in electronics timing applications for more than 40 years. The emergence of high-quality, low-cost packaging for MEMS resonators has enabled the first demonstrations of long-term stability and opened the door for commercial applications.**

I. Introduction

MEMS Resonators have been studied for more than 40 years, with continuous interest in their use as frequency references [1]. Unfortunately, the promise of MEMS resonators for these applications has always been limited by observations of unacceptable amounts of drift in the frequency of MEMS devices. For 40 years, these observations of excessive frequency drift were attributed to fundamental materials properties or fundamental limitations, and offered as justification to exclude MEMS from consideration.

The MEMS research community has been partly to blame for this perception. The research focus of the community in the early days was oriented towards innovative fabrication process approaches to produce unique geometric structures instead of on standard processes. Our literature is filled with examples of microfabricated structures that can never be produced in volume at acceptable cost.

Compounding this problem has been the absence of a serious focus on packaging. All MEMS devices are fragile, and can be damaged or significantly altered by exposure to practical environments. For example, the die separation that must happen at the end of MEMS wafer fabrication is a traumatic event for exposed structures on the surface of a wafer. The only successful MEMS products are ones where low-cost approaches to packaging of the MEMS prior to die separation have been developed. In most cases, the development of packaging processes has taken place long after the MEMS device was designed and demonstrated.

In our group, a recent effort has focused on the development of a MEMS device process that includes a wafer-scale encapsulation process [2]. At the time of this process development, our group was collaborating with personnel from the Robert Bosch Research and Technology Center in Palo Alto, CA. The goal of our effort was to develop inertial sensors and packaging processes that were 100% compatible with the manufacturing processes already in production at the main fabrication facilities used by Bosch.

The result of this approach is a wafer-scale fabrication process that provides an ultra-clean packaging environment for encapsulated resonators. Devices built in this process are extremely stable [4]; we now understand that all historical observations of drift in MEMS resonators can be attributed to adsorbates, stress, and other issues that can be addressed in clean packages. This observation has helped allowed a number of MEMS resonator companies to emerge (Discera, SiTime, Silicon Clocks, and many others).

The remaining challenges for MEMS resonators arise from the temperature coefficient of the modulus of Silicon, which gives rise to an extremely reproducible temperature dependence of frequency. The temperature coefficient of the modulus of Silicon is a well-known parameter, giving rise to a ~30 ppm/C error in frequency. With the perception of uncontrollable drift eliminated, it is time for engineering approaches to solve the remaining problems.

II. Encapsulation

MEMS Resonators must be packaged in order to eliminate the effect of adsorbates or other environmental factors on the stability of the resonant frequency. In many cases, this is achieved by bonding a “cap wafer” onto a “device wafer” after the release of the MEMS devices, but prior to the separation of the die. Bonding is usually achieved in a modest-temperature process with a glass frit or a metallic solder as the sealing material. Residual gases within the package can cause frequency shifts due to adsorbtion/desorbtion processes, and management of this problem usually relies on the use of a chemically-active getter to capture the potential adsorbate species. Despite these challenges, very large-volume inertial sensors have been built for automotive safety systems, and

978-1-4244-6400-5/10/$26.00

some companies are beginning to produce resonators for timing applications.

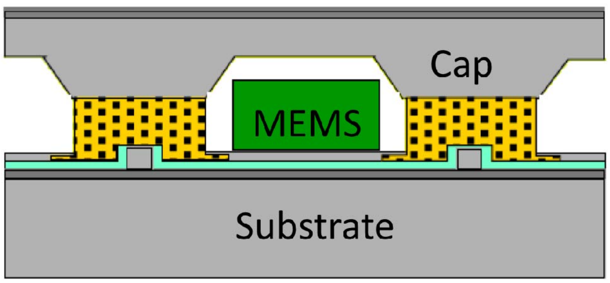

Figure 1. Illustration of a bonded-cap package design for a MEMS device. In this approach, the MEMS structure is released and then sealed at the wafer-scale by bonding of a second wafer using a glass frit or some other low-temperature sealing material.

In our process, the MEMS device fabrication and the encapsulation processes are completed at the same time in a merged process, described below.

The encapsulated MEMS Fabrication Process is illustrated in Fig. 2. We begin with a SOI Wafer and etch trenches to define the outline of the resonator. A conformal LPCVD Oxide is grown, sealing over the trenches just etched. Contacts are opened through this oxide and a 2-4 micron thick epitaxial polysilicon layer is deposited. Vents are etched in the polysilicon layer, and HF Vapor etch is used to remove the SiO2 within the structure, thereby releasing the device. Additional polysilicon is grown to re-seal the structure, and subsequent steps define and form the electrical contact vias to the device while preserving the encapsulation seal.

For stable resonators, the most important step in this process is the second epitaxial polysilicon growth, which seals the resonator within the released chamber while at temperatures over 1000C in an ultraclean environment. The residual process gasses trapped within this encapsulation react to form Si selectively on the interior Si surfaces, and the only remaining gas is H2. The exposed Si surfaces within the chamber act as getters for any other residual gas. At the completion of this step, the resonator surfaces are all clean Si, and the only residual gas in the chamber is H2, which can be driven out by annealing of the wafers in N2 environments at 400C or higher. We have shown that H2 can be driven in and out repeatedly by successive annealing steps at 400C in H2 and N2 environments.

When cooled to room temperature and operated as a resonator, these capacitively-coupled silicon resonators have shown long-term stability and repeatability under temperature cycling that is consistent with the needs of a resonant thermometer. Specifically, long-term frequency stability of better than 0.1 ppm has been demonstrated for operation at fixed temperature and through thousands of temperature cycles [4]. With the demonstration of stable, encapsulated resonators it is possible to begin work on temperature compensation in MEMS resonators.

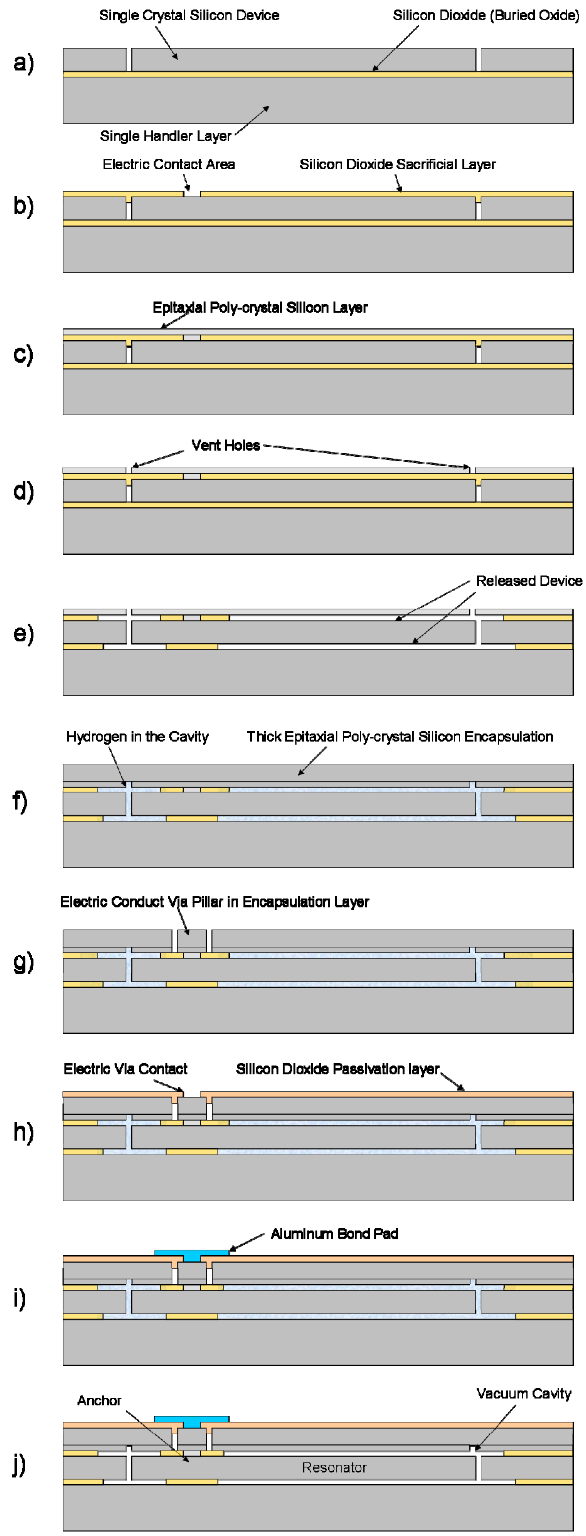

Figure 2 Illustration of MEMS Encapsulation Process.

III. Reducing the Effect of Temperature on Frequency of a MEMS Resonator

A. Compensation

The primary source of temperature-dependent error in frequency arises from the temperature dependence of the Young's modulus of Silicon, which contributes to a -30 ppm/C error in frequency. This error can be reduced by temperature control of the resonator, and by use of compensating materials, such as SiO2, or by electronic compensation methods. The use of SiO2 films for passive compensation was proposed almost 40 years ago, and provides a very attractive concept for reduction of this error source [3]. We are very fortunate in this situation that the growth of SiO2 films is perhaps the most mature thin film fabrication process, and that it is 100% compatible with our wafer-scale encapsulation process, as well as with most MEMS resonator fabrication processes and facilities. Reduction of the total temperature-induced error in MEMS frequency references by almost 2 orders of magnitude has been demonstrated for our devices using a encapsulation process [5].

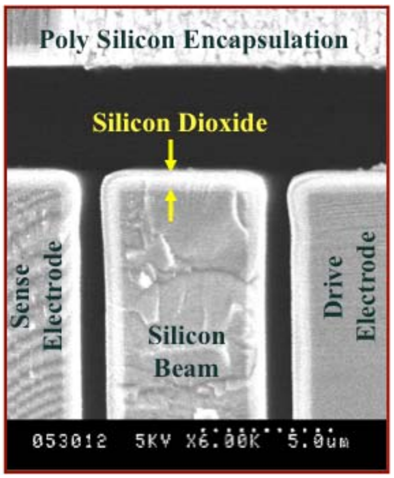

Figure 3. Encapsulated Resonator with SiO2 coating for mechanical stiffness compensation.

B. Control

The most accurate cm-scale references are temperature controlled crystal oscillators, in which a quartz crystal I suspended within a metal can package, and heated to a fixed, elevated temperature. These are usually referred to as Oven-Controlled Crystal Oscillators (OCXO). The most important element of this system is the "temperature sensor", which often arises through a 2-frequency measurement scheme [6]. However, the mechanical suspension and thermal isolation of a quartz crystal at the cm-scale leads to a need for 1-10W of heating power, and overall systems that are expensive (~$1000), and fragile. Miniaturization of the resonating element can reduce the overall size, weight, and power consumption by orders of magnitude.

Within the constraints of our encapsulation process, it is possible to build micrometer-scale planar suspensions that provide excellent thermal isolation (to reduce the power consumption) and high stiffness (to improve the shock survival). However, it is necessary to implement a thermometer within this architecture that can allow a temperature control approach to operate. In our case, we follow the example of the 2-frequency scheme used for OCXO by suspending a pair of resonators with different temperature coefficients, and using a PLL to guide the controller to operation at the crossover frequency of the 2 resonators. [7]

This work sponsored by the Defense Advanced Research Projects Agency and the Robert Bosch Research and Technology Center.

Figure 4 shows the design of a dual resonator device. A pair of resonators is suspended and heated from a common mechanical structure. The resonators have different dimensions, so that a single SiO2 film thickness can lead to a pair of resonators with different frequency-vs-temperature characteristics within a single structure.

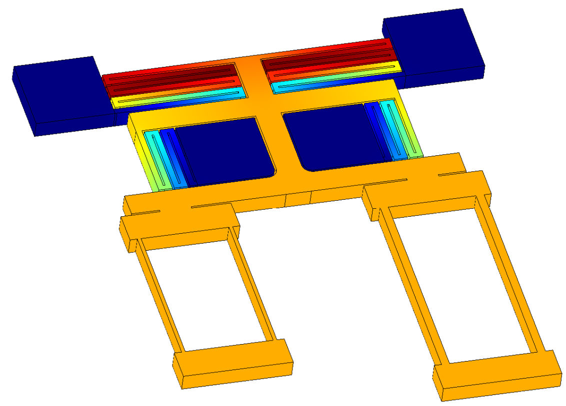

Figure 4. Illustration of a dual resonator design

Using this approach, we have shown that is possible to control the temperature of the dual resonator to better than 0.1C using less than 20 mW of heater power over the temperature range from -50 to +70C using a PCB implementation of the entire system.

The main message from all of this is that the fundamental stability of encapsulated MEMS resonators at least comparable to the best quartz crystal resonators. Furthermore, this design and fabrication process provides many significant opportunities for design and optimization of resonator design and oscillator operation. Perhaps most importantly, the technology for manufacturing of MEMS resonators is reaching a state of maturity that allows a variety of solutions to the challenges that must be overcome to address real applications.

The remaining question is : can all of this basic technology FINALLY translate to commercial insertion for MEMS resonators in electronics timing applications?

IV. MEMS Resonator Commercialization

MEMS resonators have been described as possible replacements for quartz crystal resonators for more than 40 years [1]. In the time since the first MEMS resonators, fabrication processes have significantly improved, and many candidate devices have been developed. Our claim is that the development of low-cost encapsulation and packaging capabilities has enabled resonators to reach the marketplace for the first time.

The first company to focus on commercialization of MEMS resonators is Discera (www.discera.com). Discera was founded in 2000 based on MEMS resonator research activities at the University of Michigan, and has been working to develop polysilicon resonators for commercial timing applications. This technology relies on a standard MEMS fabrication process in which devices are fabricated, released, and packaged using a bonded-cap process similar to the architecture illustrated in figure 1 above. Discera has been offering samples to potential customers for more than a year, and has begun shipping significant quantities of their product.

SiTime was started in 2005 based on the technology described in this paper (www.sitime.com). At the time of the 2010 IEEE Frequency Control Symposium, press releases from SiTime were announcing shipments of more than 20 million oscillators, along with rapid quarter-on-quarter growth in total shipments, customers, design wins, and total revenue.

Silicon Clocks was founded in 2007 based on SiGe mechanical materials (www.siliconclocks.com). The primary advantage of SiGe is that it can be deposited at <400C, which would allow deposition on pre-fabricated CMOS wafers, offering a short path to integrated products. Packaging would involve bonded caps after the CMOS+MEMS fabrication. Silicon Clocks was acquired by Silicon Labs in May 2010, triggering widespread speculation about the prospects for this particular technology to make a significant impact in the timing market.

Sand9 was founded in 2008, and is commercializing MEMS resonators and oscillators (www.sand9.com). The technological fundamentals of their potential products have not been publicly described, and samples are not yet available for independent testing. Nevertheless, Sand9 has already been successful at raising significant venture financing, and generating intense interest.

Aside from the startup company activities, Avago has introduced FBAR technology for filters in many telecommunication applications (www.avagotech.com). At the 2010 Frequency Control Symposium, Rich Ruby announced that 2 Billion FBARs have been shipped by Avago since the product introduction more than 10 years ago.

Additionally, the quartz manufacturing companies have been active in applying MEMS-like approaches to quartz fabrication, enabling miniaturization of quartz oscillators. Epson Toyocom has announced their QMEMS technology, and other companies are exploring ways to push quartz materials into modern, lower-cost manufacturing to enable miniaturization, integration and insertion into ever-smaller portable electronic devices.

It is, of course, possible to argue the semantics of including FBARs and QMEMS-based products as "MEMS successes" in the timing market. However, even if we set these approaches aside, it is clear that Discera, SiTime, and others are having impact today. After 40 years of effort, it does appear that MEMS is finally having success in the electronics timing industry.

"Will MEMS Replace Quartz?" – this question was asked and discussed at length in a panel session at the 2010 IEEE Frequency Control Symposium. There was a very wide range of opinions offered. In fact, there was agreement that MEMS is already beginning to replace quartz in some products, so most of the discussion focused on the range of the impact of MEMS in applications. Strong opinions were offered that MEMS will never replace quartz for the extreme low-cost marketplace, or for the extreme high-performance applications. However, countering opinions suggested that, with the recent demonstrations of silicon-based approaches for structures and packaging, or for enhanced stability architectures, there are no fundamental barriers to the range of MEMS intrusion into the quartz application space. Time will tell!

REFERENCES

[1] H.C.Nathanson, W.E. Newell, R.A. Wickstrom, J.R. Davis, "The Resonant Gate Transistor", IEEE Trans. Electron Devices 1967, 14 (3), 117–133.

[2] R.N. Candler, W.T. Park, H.M. Li, G. Yama, A. Partridge, M. Lutz, and T.W. Kenny, "Single Wafer Encapsulation of MEMS Devices", IEEE Transactions on Advanced packaging 26, 227 (2003).

[3] B.S. Berry and W.C. Pritchet, "Temperature Compensation for Constant-Frequency Electromechanical Oscillators", IBM Technical Disclosure Bulletin, Vol. 14, #4, P. 1237-8 (1971).

[4] B. Kim, R.N. Candler, M.A. Hopcroft; M. Agarwal, WT Park, T.W. Kenny, "Frequency stability of wafer-scale film encapsulated silicon based MEMS resonators" Sensors and Actuators A (Physical), 136, 125 (2007).

[5] R. Melamud, S.A. Chandorkar, B. Kim, HK Lee, J. Salvia, G. Bahl, MA Hopcroft, and TW Kenny, "Temperature-Insensitive Composite Micromechanical Resonators", IEEE JMEMS 18, 1409 (2009).

[6] S. Schodowski, "Resonator Self-Temperature-Sensing Using a Dual-Harmonic-Mode Crystal Oscillator," Proc. 43rd Annual Symposium on Frequency Control, pp. 2-7, 1989, IEEE Catalog No. 89CH2690-6.

[7] 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", IEEE JMEMS 19, 192 (2010).