RECENT PROGRESS IN SILICON MEMS OSCILLATORS

Wan-Thai Hsu
Discera, Inc.
655 Phoenix Dr., Ann Arbor, MI 48018, USA
E-mail: *whsu@discera.com*

Abstract

This paper first reviews key milestones in the making of silicon MEMS oscillators and how MEMS resonators can be used as frequency references for electronic systems, starting from silicon resonators device designs with different fabrication processes, to wafer level packaging technologies, to the robustness of volume manufacturing processes. Secondly, as final products, various MEMS oscillators from various companies are compared with quartz crystal oscillators in terms of jitter, power consumption, and temperature stability. Finally, to ensure the performance is good for real electronics applications, silicon MEMS oscillators not only have passed standard JEDEC reliability tests such as aging, solder reflow, thermal shock, and autoclave, but also have been demonstrated in several electronic systems.

INTRODUCTION

Almost all electronic systems need to reference a frequency reference source for synchronization between function blocks as well as between systems. This frequency reference acts like the heart beat in human body – one could not live without it, and could live healthily without its stability. Over the past few decades, quartz crystals have been providing accurate frequency references for many electronic systems. However, although quartz crystals are widely used in electronic systems, they are essentially mechanical vibrating devices that provide their stable natural resonance frequencies. However, compared to electronic circuits, they are large in size, hard to batch process, and hard to integrate on a chip.

With the progress of MEMS technologies in the past decade, micro-scale mechanical structures can be fabricated on silicon wafers. With further development of interface and conditioning circuitry, these tiny silicon MEMS resonators have been proven stable and reliable in providing frequency reference sources for products ranging from commercial, automotive, and some military applications, with the features of being thinner, cheaper, lower power, and easier for system integration.

This presentation first reviews key milestones in the making of silicon MEMS oscillators and how MEMS resonators can be used for frequency reference of electronic systems, starting from silicon resonators device designs with different fabrication processes, to wafer level packaging technologies, to the robustness of volume manufacturing processes. Secondly, as final products, various MEMS oscillators from various companies are compared with quartz crystal oscillators in terms of jitter, power consumption, and temperature stability. Finally, to ensure that the performance is good for real electronics applications, silicon MEMS oscillators not only have passed standard JEDEC reliability tests such as aging, solder reflow, thermal shock, and autoclave, but also have been demonstrated in several electronic systems, including a high-performance camcorder.

Silicon micro-mechanical resonators have been replacing some of the quartz crystal oscillators in various electronic systems due to their advantages described above. In fact, miniaturization, low cost, and system integration are the major drivers. At the end of this paper, the trend and the future of silicon MEMS oscillators will be presented from the angle of performance enhancement.

SILICON MICRO-MECHANICAL RESONATORS

MEMS resonators are defined as micro-machined mechanical structures that vibrate at their natural resonant frequency when excited by an external force. A single structure may have several different mechanical mode shapes or frequencies, and the drive force may arise from electrostatic, piezoelectric, optical, mechanical vibration, or magnetic stimuli. Regardless of the configuration of the resonator, for oscillator applications, it should be operated in a mode that yields a high quality factor, minimizes motional impedance, and offers a high dynamic range (typically bounded by circuit sensitivity on the low end and transducer linearity on the high end).

One of the earliest works that MEMS resonators researchers reference is Nathanson's article "The resonant gate transistors" published in 1967 **[1]**. In this work, gate oxide of a transistor was removed to allow a metal gate to mechanically vibrate. This vibration provided high quality factor (*Q*) frequency selection. A 12-kHz integrated oscillator was demonstrated together with 90-150 ppm/°C of thermal stability.

Early developments of silicon micromechanical resonator technologies are on low frequency oscillators **[2]** as well as filters **[3]** ranging from kilohertz to low megahertz in frequency. Low frequency applications typically employ folded-beam comb-drive resonators shown in Figure 1 for 32.768 kHz real-time clock (RTC) applications. Commercial grade oscillators operating in this range must be capable of working with very low electrostatic transducer bias voltages and consume very little power. A state-of-the-art RTC oscillator was presented in **[4]**, where the resonator operates at 1.5V, and the IC consumes less than 1 μA of current.

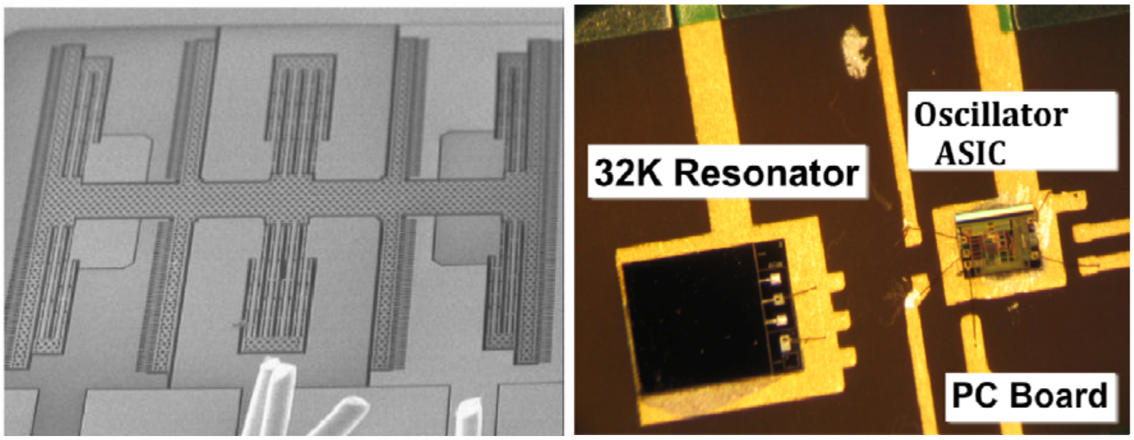
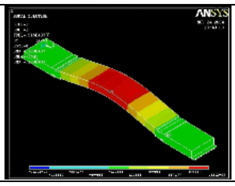
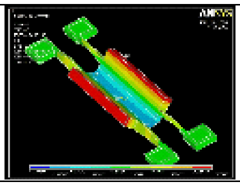
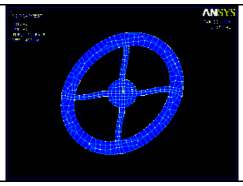
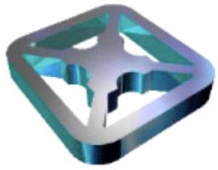
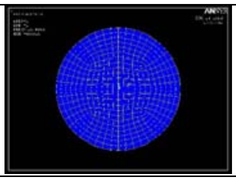
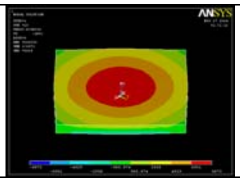


Figure 1. (a) 32.768 kHz comb-drive resonators; (b) wafer level packaged resonator with oscillator circuits on PCB.

Table I. Various modes of resonator beams.

	CC Beam	FF Beam	Circular	Square [5]
Flexural Mode				
	1D	2D	2D	
Bulk Acoustic Mode				

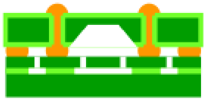
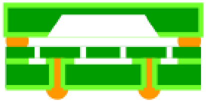
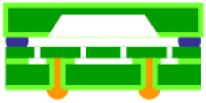
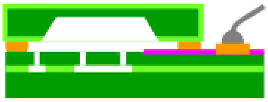
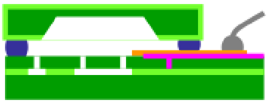
Generally, resonators can be categorized into two major modes: flexural mode and bulk acoustic mode. The simplest flexural mode clamped-clamped beam, shown on the next line of the table, overcomes these scaling limits with a simpler structure with less mass and higher stiffness, exhibiting a Q as high as 8,000 at 9.8 MHz **[6]**. However, scaling the clamped-clamped beam to higher frequencies such as 50 MHz quickly degrades performance, as anchor dissipation limits the Q. The free-free beam resonator overcomes this limitation by using a virtual floating beam whose supports are designed to minimize acoustic loss to the substrate. Using this technique, free-free beam resonators have shown Q as high as 7.4k at 92 MHz **[7]**, and its excellent performance and versatility have made it the resonator of choice for some current generation commercial oscillator products.

However, flexural mode resonators also hit their scaling limits around 100 MHz, as the dimensions required for higher frequencies become difficult to control and motional impedance grows rapidly. Moving down the table, bulk acoustic mode resonators get around these limitations by employing resonant modes with much higher effective stiffness, increasing the operating frequency. Such devices require small lateral gaps fabricated by processes such as that presented in **[8]** in order to ensure efficient electrostatic transduction. Published devices include the disk resonator operating in radial **[9]** and wine-glass modes **[10]** and the square resonator in extensional mode **[11]**. Wineglass mode resonators have demonstrated quality factors as high as 98K in vacuum, and 70K in air, which is more than sufficient for oscillator applications.

Electrostatically transduced resonators face inherent limitations on motional impedance, which can grow unacceptably large as resonators are scaled to higher frequencies. The final resonators in the table utilize piezoelectric transduction to offer both lower impedance and better linear power handling than electrostatic devices. Surface or bulk micromachined aluminum nitride (AlN) resonators **[12]** and AlN-based FBAR resonators also show good potential for oscillator applications **[13,14]**. However, compared to silicon resonators, piezoelectric resonators are in relatively early stages of development in terms of structural optimization for quality factor and process capabilities for reference grade applications.

All the above resonators are very small in size. Therefore, they are very sensitive to air molecules. From the stability point of view, just like quartz crystal resonators, silicon resonators always need to be sealed in a hermetic or vacuum environment. Based on the processes and materials for sealing, wafer level vacuum packaging for MEMS resonators (also applied to other MEMS devices such as gyroscopes and

Table II. Interconnection methods versus sealing material in wafer bonding technologies.

Seal Material	Conductive	Non-conductive
Connect from Top		
	• Sealing and interconnection done at the same time (can be same material) • Interconnection process is separated from MEMS	• Conductive interconnection formed at the same time as non-conductive seal • Interconnection process is separated from MEMS
Connect from Bottom		
	• Sealing and inter-connection done at the different time → may use different material to optimize the processes • Process may impact MEMS device	• Sealing and inter-connection done at the different time • Process may impact MEMS devices
Connect from Side		
	• Need isolation layer btw inter-connection & sealing material • Need buried interconnection • Planarization of dielectric needed	• No isolation needed between interconnection & sealing material • Seal needs to overcome the topography of interconnection

accelerometers) can be categorized into two types: wafer bonding and deposition sealing. Wafer bonding means MEMS wafers are aligned and bonded together with a cap wafer under vacuum environment. Deposition sealing means the air in the device cavity is first evacuated through the holes on the cavity, and the cavity is then sealed by depositing material into the holes. Since these two methodologies have their advantages and disadvantages, normally the choice of packaging technologies is based on the resonator design as well as resonator fabrication processes, vacuum requirements, interconnection structures, final package design, and product specifications.

Systems need the access to the MEMS devices sealed in the vacuum cavity. Therefore, interconnection design is considered an essential part of the wafer level packaging processes. Table II presents a matrix of three various interconnects with three different directions – top, bottom, and sideways, versus two major types of intermediate materials – conductive and nonconductive. This table also includes the features as well as pros and cons of each combination. For example, the interconnections would be connected through the cap wafers or through the MEMS wafers if through wafer via technologies are available. Meanwhile, if the interconnections are taken from sideways, part of the cap wafers need to be removed in order to expose the bonding pads. Figure 2 shows one example of wafer level packaging for MEMS resonators.

In summary, the requirements for vacuum package of MEMS resonators are the following: (1) the impacts of encapsulation processes to the resonator performance must be minimized; (2) resonators must be encapsulated on wafer level for cost reasons, and expect to have >30% cost reduction on packaging for the next generation devices; (3) the *Q*'s of the resonators must not degrade after 10 years; and (4) environmental robustness, including stress, shock, vibration, shear force, corrosion, and thermal cycling. Choosing the technologies and the designs smartly will minimize the cost as well enhance the performance and manufacturing yield.

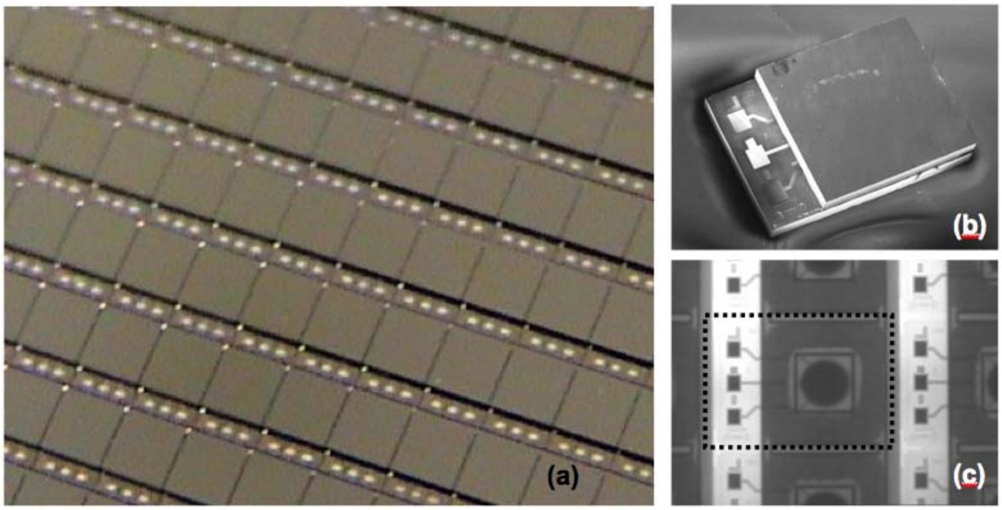


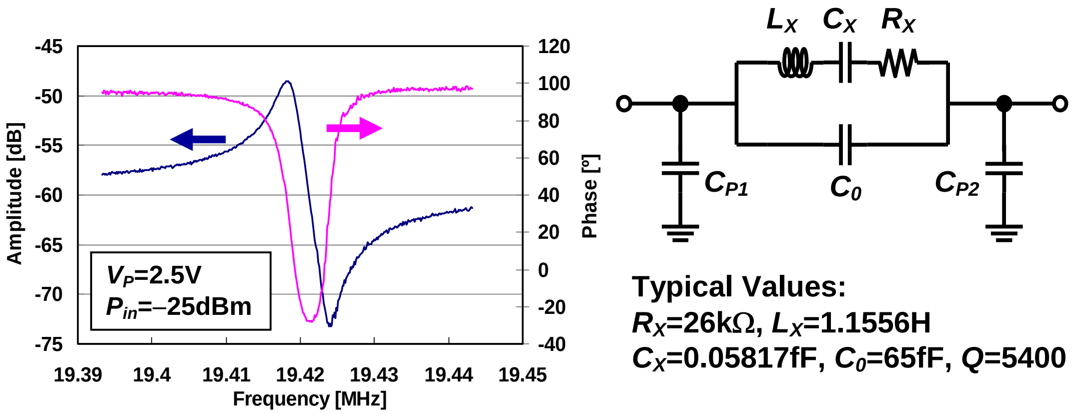
Figure 2. Example of wafer level packaged silicon MEMS resonators.

SILICON MEMS OSCILLATORS

Oscillators normally consist of a high-Q frequency reference tank, which determines the frequency and the stability of the oscillator, and a circuit that sustains the oscillation. Figure 3 shows a typical measured spectrum of the MEMS resonator and its equivalent circuits. As shown, the spectrum is similar to that of a quartz crystal resonator except for its (1) higher motional resistance (R_x), (2) lower power handling capability (because of the small size), and (3) DC bias voltage required to operate the resonators. As a result, instead of Colpitts or Pierce architecture, a transimpedence amplifier is typically used for sustain the oscillation.

The frequency of the resonators is determined by both material properties and geometry of the resonators – exactly the same as for quartz crystal resonators. Typically, depending on the systems, the oscillator output frequency needs to be within ppm (i.e. from 1 ppm to 100 ppm) to the target frequency for system applications. However, since semiconductor processes are used for MEMS resonator fabrication, the process variation of film thickness, lithography, and etching made the frequency of the resonators prior to trimming vary between ±1% and ±10%, depending on the process control.

Moreover, silicon resonators typically exhibit monotonic temperature dependent curves. This temperature dependence is mainly due to the temperature coefficient of Young’s modulus of the resonator structure. As a result, depending on the resonator material, the temperature coefficients range from -40 ppm/^{o}C to -15 ppm/^{o}C. In comparison to the temperature characteristic of quartz crystal resonators, as shown in Figure 4, MEMS resonators show a straight line with a slope larger than even the worse case of AT-cut quartz crystals. Based on experiment results, the TC_f of the MEMS resonator can be maintained as a straight line from -180^{o}C to 150^{o}C. As said earlier, the accuracy of the frequency needs to be within 10~100 ppm across all environmental conditions for XO applications. Therefore, the temperature coefficient of frequency (TC_f) of the MEMS resonators needs to be compensated.



(a) **(b)**

Figure 3. (a) Measured spectrum of a MEMS resonator; (b) its equivalent model and typical numbers for *RLC* model.

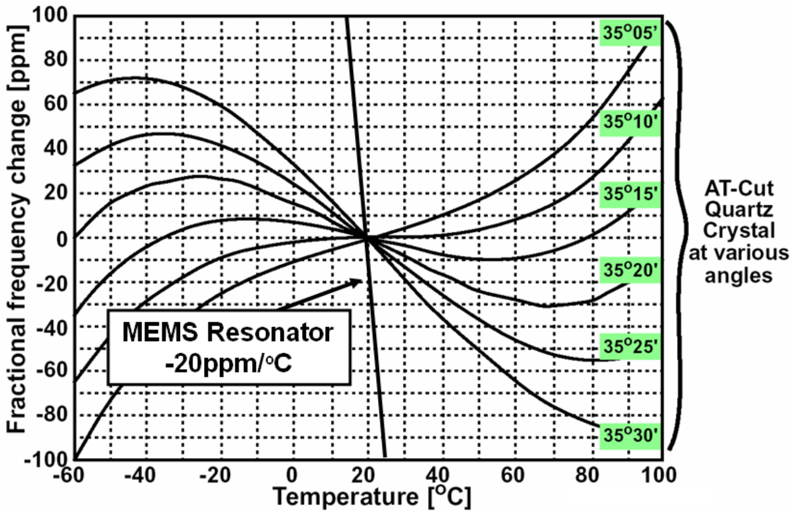


Figure 4. Frequency variations versus temperature of quartz crystals and a MEMS resonator.

Figure 5 shows the system diagram of a digitally compensated MEMS oscillator. As shown, a MEMS resonator is connected to an IC. The reference oscillator, which is basically a transimpedance amplifier, accommodates the larger motional resistance and smaller phase shifts seen in MEMS resonators over the temperature range and over all process corner conditions. The output frequency of the reference oscillator is then fed into a fractional-N synthesizer. The main loop for the fractional-N synthesizer consists of a charge pump, a phase-frequency detector, an on-chip loop filter, a wideband VCO, and a programmable divider. The programmable divider is modulated by the ΣΔ block. The digital control, programming, and temperature compensation are all monitored by the control circuits. Control logic controls the blocks based on the temperature. All functionality and communication are achieved through four pins, Enable, VDD, GND, and Output, which are the standard oscillator pins.

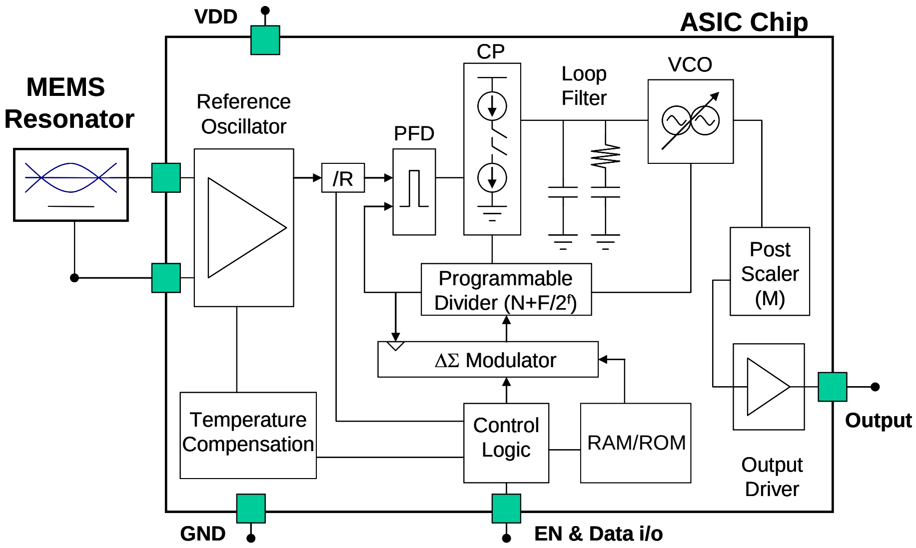


Figure 5. System diagram of a digitally compensated MEMS oscillator.

The output frequency of the reference oscillator is measured at room temperature. This frequency is compared to the target frequency. Then the control logic will calculate numbers to be set in the VCO, dividers, and post-scaler and store those numbers in the memory. Same steps are performed at another temperature. Based on these two sets of parameters, a look-up table can be easily established simply because the resonator shows monotonic temperature characteristics. The line that connects the two calibration points can set a line with a proper slope (TC_f) to extended temperatures. Thus, the output frequency of the oscillator is set to the target and is adjusted according to the temperature. If the TC_f is predictable, only one calibration is needed.

Figure 6 shows the temperature dependence of a digitally compensated programmable MEMS oscillator. It shows a total 7 ppm frequency variation in the typical commercial range of temperature (–40^{o}C to 85^{o}C). Compared to digitally compensated programmable quartz crystal oscillators with a total 25 ppm frequency variation across the temperature, clearly MEMS oscillators are qualified for an XO level of applications.

However, although digital compensation is the best and the easiest temperature compensation method, one drawback to using digital temperature compensation is that the PLL synthesizer and VCO introduce more phase noise into the oscillator output spectrum. This increase in phase noise current prevents MEMS oscillators from having low phase noise and RF applications. Figure 7 compares phase noise measurement of a MEMS oscillator before and after PLL frequency adjustment, programmable quartz crystal oscillators, and pure quartz crystal oscillators.

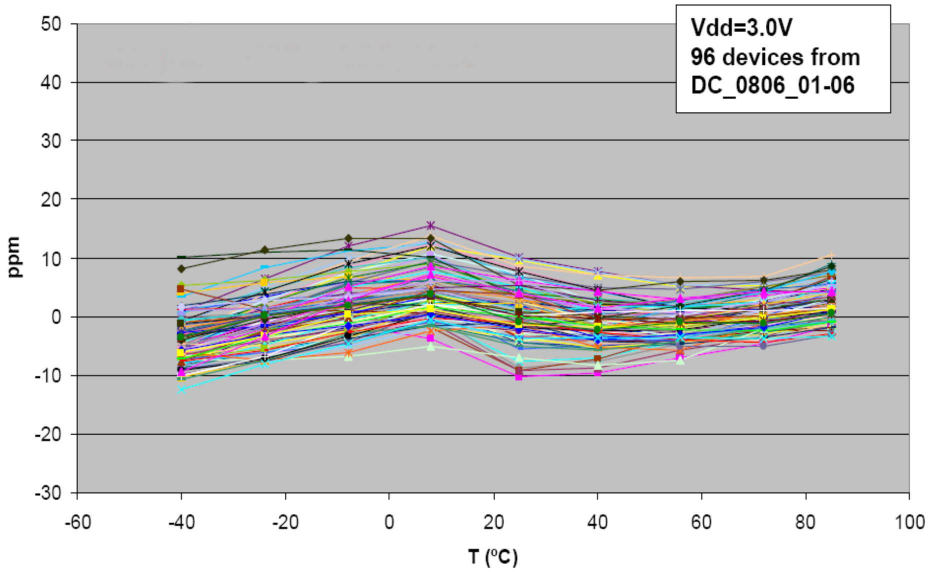


Figure 6. Typical temperature characteristics of a digitally compensated MEMS oscillator.

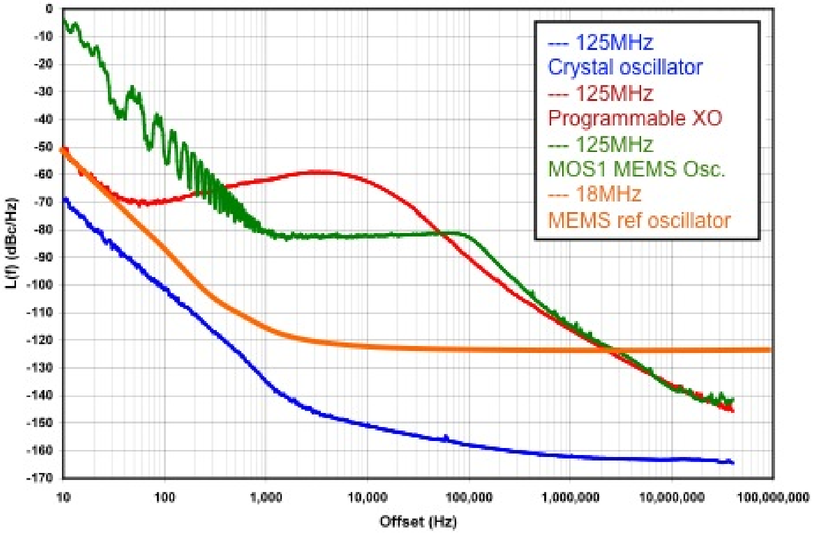


Figure 7. Measured phase noise of quartz oscillators, programmable quartz oscillators, programmable MEMS oscillators, and uncompensated MEMS oscillators.

So far, MEMS oscillators have met all the requirements respect to phase noise, jitter, temperature stability, power consumption, and reliability for the mainstream 1- to 125-MHz XO segment. This segment covers high-volume applications, including consumer electronics, I/Os such as USB, computing, etc. The data sheet is shown in Table III. However, the next application target for MEMS oscillators is to reach the accuracy requirements of a TCXO, which typically exhibits < 2 ppm frequency variation across all the environmental parameters, and -130 dBc/Hz at 1 kHz offset and -150 dBc/Hz far from carrier of phase noise. Most importantly, the power consumption of the oscillator needs to be low. Therefore, three requirements need to be satisfied in order to promote MEMS oscillators for TCXO applications: (1) temperature stability, (2) low phase noise, and (3) frequency accuracy. MEMS oscillators from different research groups may have reached individual specifications, but none has demonstrated meeting three of them at the same time. As a result, this is one of the first and probably the most important research goals for MEMS oscillators.

RELIABILITY OF SILICON MEMS OSCILLATORS

A resonator reliability test was conducted with both packaged silicon MEMS resonators and plastic packaged oscillators. They were both tested against standard semiconductor reliability specifications.

(1) Autoclave: singulated resonators are placed under 2 atmospheres at 121°C based on JEDEC standard for 336 hours. This test provides the info as to whether the sealing of the resonators could maintain good vacuum for its life time of 10 years. Fortunately, the Q of the resonator is the best parameter to monitor vacuum failure, so we simply test the Q of the resonators before and after the autoclave. As shown in Figure 5a, the Q's of the resonators remained at around 6,000 and did not degrade.

(2) High temperature storage life (HTSL): singulated resonators are placed into 150°C oven for 1000 hours. The major purpose of this test is to prove that there is no residual stress in the sealing that causes de-lamination. The results in Figure 5b showed the Q's remain the same after a 1000-hour HTSL test.

(3) Bond strength and shear force: in order to test if the resonators can survive the pick and place or other assembly processes with automatic tools, typical pull and shear force was applied to the resonators. The results showed that the strength of the packaged resonators far exceeded the force generated by assembly tools.

Tests were conducted mainly to identify package or assembly related failures after an accelerated test. The accelerated conditions include a moisture soak at 121°C, preconditioning at 125°C, autoclave (note: this autoclave is a whole package autoclave; the MEMS resonators were enclosed in plastic or ceramic packages), and liquid thermal shock between –55°C and +125°C. These conditions are based on JEDEC standards. All packaged MEMS oscillators passed the screening test.

In addition to the mechanical reliability, silicon MEMS oscillators were tested against the product specifications based on the standards listed in Table IV. As shown, MEMS oscillators have been taken into more severe conditions than quartz crystal oscillators either by having more hours for the same test, or by having additional tests that were not usually applied to quartz crystals. For example, Highly Accelerated Stress Testing (HAST) is to place devices in high temperature, high humidity, and high pressure as a destructive environment for standard high reliability testing of integrated circuits. The maintenance of high humidity at temperatures above 100°C allows for extreme acceleration, up to a factor of 50, of corrosion mechanisms due to moisture. The fact that MEMS oscillators passed HAST (also a 1000-hour THBT as verification) indicate the oscillators will remain in specification under normal operation for 20 years.

Some more extreme reliability tests were conducted with MEMS oscillators. Since the mass of silicon MEMS resonators is on the order of 10^{-11} kg and the stiffness of the resonator beam is as high as tens of thousands of newtons, MEMS resonators are able to easily survive under high acceleration and high-G shock conditions. In simulation, MEMS resonators only deviate less than 100 Å under a 100,000-G shock. Therefore, MEMS oscillators were tested under military standards on shock resistance at 14,000

G, operation vibration at 50 G, and constant acceleration at 25,000 G with 100% survivability. These facts qualify MEMS oscillators for harsh environment applications.

CONCLUSIONS

The promise of MEMS resonators has been anticipated for a long time. Finally, the technology is commercially viable and is being rolled out as we speak. Industrial analysts have created a new category for MEMS resonators in their reports and expect this to be a high volume product. While quartz crystal technology is very important, relevant, and will continue to have its share of the market, MEMS resonators have an opportunity to make a big impact on the consumer markets, and will grow and evolve over time.

REFERENCES

[1] H. Nathanson, W. E. Newell, R. A. Wickstrom, and J. R. Davis, Jr., 1967, *"The resonant gate transistor,"* **IEEE Trans. Electron Devices, ED-14,** 117–133.

[2] C. T.-C. Nguyen and R. T. Howe, 1993, "*CMOS Micromechanical Resonator Oscillator,"* in Technical Digest of the IEEE International Electronic Devices Meeting (IEDM), 5-8 December 1993, Washington, D.C., USA (IEEE Publication), pp. 199-202.

[3] K. Wang, A.-C. Wong, and C. T.-C. Nguyen, 2000, "*VHF Free-Free Beam High-Q Micromechanical Resonators,"* **IEEE/ASME Joural of Microelectromechanical Systems, 9,** 347-360.

[4] K. Cioffi and W.-T Hsu, 2005, *"32KHz MEMS based Oscillator for Ultra-low Power Applications,"* in Proceedings of the 2005 Joint IEEE International Frequency Control Symposium (FCS) and Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 29-31 September 2005, Vancouver, Canada (IEEE 05CH37664), pp. 551-558.

[5] *http://www.sitime.com*

[6] F. D. Bannon, J. R. Clark, and C. T.-C. Nguyen, 2000, *"High-Q HF micromechanical filters,"* **IEEE Journal of Solid-State Circuits, 35,** 512-526.

[7] K. Wang, A.-C. Wong, and C. T.-C. Nguyen, 2000, "VHF Free-Free Beam High-*Q* Micromechanical Resonators," **IEEE/ASME Journal of Microelectromechanical Systems, 9,** 347-360.

[8] W.-T. Hsu, J. R. Clark, and C. T.-C. Nguyen, 2001, "*A Sub-micron Capacitive Gap Process for Multiple-Metal-Electrode Lateral Micromechanical Resonators*," in Technical Digest of the 14th IEEE International Conference on Micro Electrical Mechanical Systems (MEMS), 21-25 January 2001, Interlaken, Switzerland (IEEE Publication 01CH37090), pp. 349-352.

[9] J. R. Clark, W.-T. Hsu, and C. T.-C. Nguyen, 2001, "High-Q VHF Micromechanical Contour-Mode Disk Resonators," in Technical Digest of the International Electronic Devices Meeting (IEDM), 10-13 December 2000, San Francisco, California, USA (IEEE Publication 00CH37138), pp. 393-396.

[10] M. A. Abdelmoneum, M. U. Demirci, and C. T.-C. Nguyen, 2003, "Stemless wine-glass mode disk micro resonators," in Technical Digest of the 16th Annual IEEE International Conference on Micro

Electrical Mechanical Systems (MEMS), 19-23 January, Kyoto, Japan (IEEE Publication 03CH37426), pp. 698-701.

[11] V. Kaajakari, T. Mattila, A. Oja, J. Kiihamäki, H. Kattelus, M. Koskenvuori, P. Rantakari, I. Tittonen, and H. Seppä, 2003, *"Square Extensional Mode Single-Crystal Silicon Micro Mechanical RF-resonator,"* in Proceedings of Transducers '03, the 12th International Conference on Solid-State Sensors and Actuators, 8-12 June 2003, Boston, Massachusetts, USA (IEEE Publication), pp. 425-432.

[12] G. Piazza, P. J. Stephanou, J. M. Porter, M. B. J. Wijesundara, and A. P. Pisano, 2005, *"Low motional resistance ring-shaped contour-mode AlN piezoelectric micromechanical resonator for UHF applications,"* in Proceedings of the 18th IEEE International Conference on Micro Electrical Mechanical Systems (MEMS), 30 January-3 February 2005, Miami, Florida, USA (IEEE Publication), pp. 20-23.

[13] A. P. S. Khanna, E. Gane, T. Chong, H. Ko, P. Bradley, R. Ruby, and J. D. Larson, 2002, *"A Film Bulk Acoustic Resonator (FBAR) L Band Low Noise Oscillator for Digital Communications,"* in Proceedings of the 32nd European Microwave Conference (EuMC), 4-6 October 2002 Milan, Italy (IEEE Publication), 3 pp.