The New Heart Beat of Electronics - Silicon MEMS Oscillators

Wan-Thai Hsu and Minfan Pai*
Discera Inc.
655 Phoenix Dr., Ann Arbor, Michigan, 48108, USA
*1961 E Concourse Dr., San Jose, California, 95131, USA
whsu@discera.com

Abstract

All electronic systems need a clock source for synchronization between sub-systems as well as between systems. This clock source is acting like the heart beat in human body – one could not live without it. Over the past few decades, quartz crystals have been providing us very accurate frequency references in timing and frequency control world. With the development in the past decade, silicon MEMS technology has reached a matured level to be able to provide reliable clock sources for electronic systems – only thinner, cheaper, and easier integration. This paper reviews some key issues that have been resolved for commercializing silicon MEMS oscillators. In the near future, MEMS oscillators will be the heart of electronics that system design engineers would prefer to use.

Introduction

In the past few decades, almost no doubt when a designer designs a chip that needs frequency reference, he/she naturally reserve pins for quartz crystals. Quartz crystal is essentially a mechanical vibrating device that provides good selection and good stability of frequency for electronic systems. However, they are large in size, hard to be batch processed, and hard to be integrated on chip. On the other hand, MEMS resonator, also a mechanical resonator, is fabricated on top of silicon wafer with CMOS compatible processes and materials, providing thinner, cheaper, and lower power timing solution for great potential for integration.

In literature, MEMS resonators aiming for oscillator applications range from low kHz to GHz in frequency. An SOI based folded-beam comb-drive resonators that resonate at 32.768 kHz are used for real-time clock (RTC) in electronic systems or in watches. The state-of-art RTC oscillator was presented in [1], where the resonator can be operated at 1.5V and the IC only consumes less than 1μA of current. For oscillators in MHz range, a simple flexural beam resonators with simple surface micromachining processes exhibited good phase noise performance at 70MHz as shown in [2].

Other than flexural type of resonator, researchers also have achieved fairly good oscillator performances with bulk acoustic mode resonators – meaning the resonators were vibrating with their whole bodies deforming. As shown in [3], square resonator in extensional mode demonstrated the first MEMS oscillator meeting the phase noise specification of GSM, although without temperature compensation and with too high of dc bias. Further improvement was shown in [4], where array of disk resonators vibrating at wine-glass mode were hard-coupled together for maximizing the output power. This oscillator also reach the phase noise target, although, again, without temperature compensation and frequency tuning.

This paper first describes, in a practical way, how MEMS resonators can be used for frequency reference of electronic systems, starting from silicon resonators device operation, wafer level packaging technologies, to the reliability of volume manufacturing processes. Secondly, MEMS oscillators are compared with quartz crystal oscillator counter parts in terms of jitter, power consumption, and temperature stability. At last, 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 including a high performance camcorder.

Silicon MEMS Resonators

As described in previous session, resonator designs for oscillator applications can be categorized based on the modes of vibration – basically flexural mode and bulk acoustic mode. As shown in Figure 1, flexural mode includes folded beam, clamped-clamped beam, free-free beam, and ring resonators. Typically flexural mode resonators cover the frequency less than 100MHz due to the limit of resonator's mechanical stiffness. Therefore, bulk acoustic mode resonators become one of the keys to push resonator frequency above 100MHz. This type of resonators includes disk resonators with both contour and wineglass modes, and square resonators with extension and deformation modes. Environmental insensitivity and manufacturability are two of the most important factors in the design. Therefore, almost all resonators in Figure 1 have symmetrical structure for (1) optimization of quality factor (Q), which defines how good a

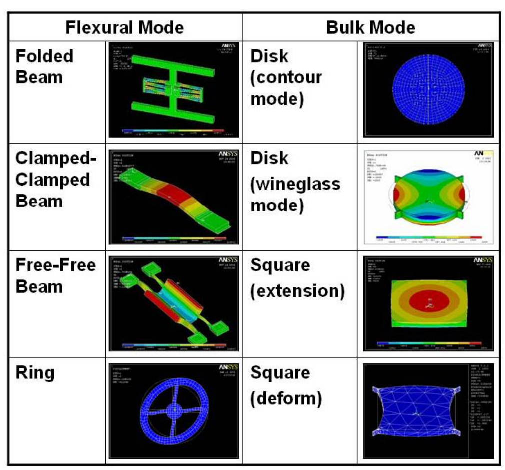

Figure 1 Matrix of micromechanical resonators and their mode shapes

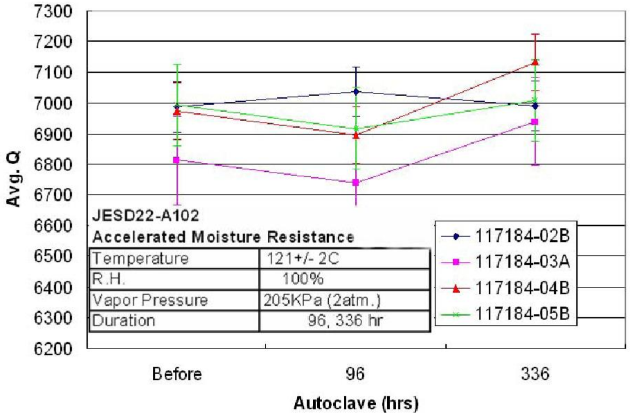

Figure 5 Resonator Q's after 336 hour standard autoclave test

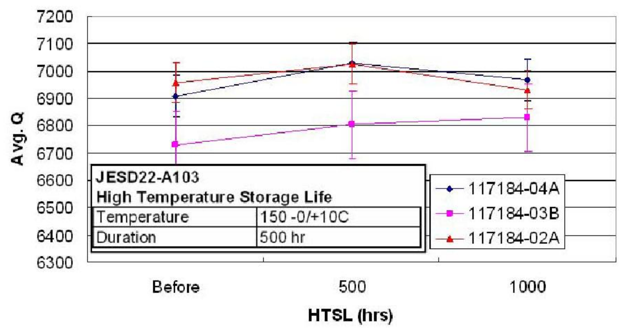

Figure 6 Resonator Q's after 1000 hour high temperature storage life (HTSL) test

model the spectrum by using a simple *RLC* circuit model shown in Fig. 2(c). Note that this model is a 2nd order system that is the same as the mechanical system shown in Fig. 2(d). The L_x, C_x, and R_x are related to the effective mass, stiffness, and damping, respectively. C_0 is the feed-through capacitance and C_1 and C_2 are both parasitic capacitance. This circuit model is the most basic building block of the resonator.

Since the mass of a MEMS resonator is on the order of 10^{-11}kg, frequency and quality factor of the resonator are easily affected by the air molecular surrounding it. Therefore, vacuum level under which the resonator is operated not only affects the resonator performance, but also affects resonator's long term reliability. Q versus vacuum level of two different resonators is characterized from 1 μTorr to 100 Torr. As shown in Figure , the Q's of low frequency 32 kHz folded beam resonators started degrading at around 2mTorr. On the other hand, due to larger mechanical stiffness, hence less sensitive to air molecular damping, 19 MHz resonators hold up their Q till 2 Torr. As a result, MHz resonators have less vacuum packaging requirements. Although some bulk acoustic mode resonators can be operated at atmosphere, hermetic encapsulation is still needed for environmental protections. Low frequency flexural resonators require higher vacuum level since the air damping impacts on compliant resonators more than the resonators with larger stiffness.

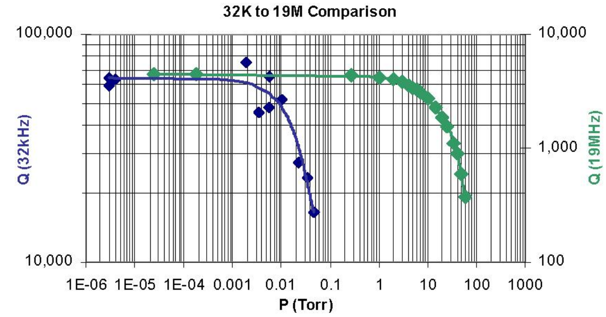

Figure 3 Vacuum packaging requirements for different MEMS resonators

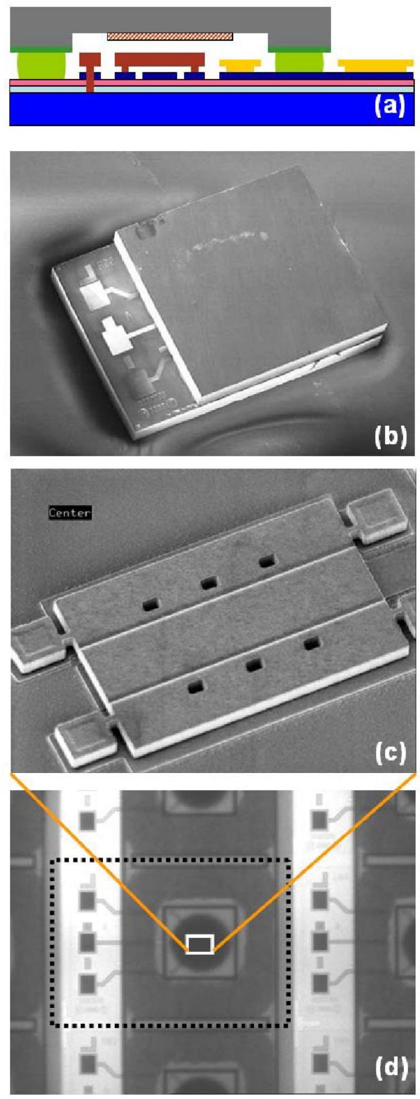

Figure 4 (a) Cross section and (b) perspective view of a packaged and singulated resonator, (c) and (d) show the size of the resonator element related to the package

Multiple technologies can fulfill the requirements of packaging, ranging from wafer bonding, through wafer via, thick-epi encapsulation. Choosing the technologies and the designs smartly will minimize the cost as well enhance the performance and manufacturing yield.

An example of fabricated and singulated MEMS resonator is shown in Figure 4. As shown, the resonator is encapsulated inside a vacuum cavity and is connected to external bonding pads via interconnections. This MEMS resonator can serve as a stand-alone frequency reference component and can be placed on top of larger processors chips inside a conventional QFN package. Therefore, the following reliability tests are necessary at this stage.

(1) Autoclave: singulated resonators are placed under 2 atmosphere at 121°C based on JEDEC standard for 336 hours. This test provides the info whether the sealing of the resonators could maintain good long term vacuum during 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 5, 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 6 showed the *Q*'s remain the same after 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 [5].

Table I Electrical parameter comparison of a MEMS oscillator vs. a quartz crystal oscillator

			Quartz (SG8002) 33.000MHz			MEMS (MOS1-S2) 33.000MHz		
Test Parameters	Conditions	Units	Vdd (3.0 V)	(2.7 V)	(3.3 V)	Vdd (3.0 V)	(2.7 V)	(3.3 V)
Current	+25C, 15pF load	mA	6.81			4.54		
Output High	+25C, 15pF load	V	2.97	2.70	3.26	2.94	2.64	3.22
Output Low	+25C, 15pF load	V	-0.10	-0.08	-0.11	-0.05	-0.04	-0.06
Output Symmetry	+25C, 15pF load	%	51.62	51.89	51.40	49.60	49.53	49.69
Rise Time	+25C,15pF,10-90% Vdd	ns	1.59	1.78	1.49	1.62	1.68	1.56
Fall Time	+25C,15pF,10-90% Vdd	ns	1.62	1.84	1.49	1.18	1.23	1.15
RMS Period Jitter	+25C, 10,000 cylces	ps	25.38	28.64	22.98	29.22	27.58	27.80
pk-pk Period Jitter	+25C, 10,000 cylces	ps	152.28	171.84	137.88	175.32	165.48	166.80
Cycle-Cycle Jitter	+25C, 10,000 cylces	ps	44.57	50.15	40.26	47.47	45.25	43.35

Silicon MEMS Oscillators

MEMS oscillator consists of an encapsulated MEMS resonator as the frequency reference and an integrated circuits for sustaining a stable output frequency at all environmental conditions. Both of these two elements are connected and enclosed in a package ranging from traditional ceramic package for timing circuits, low cost QFN package, and

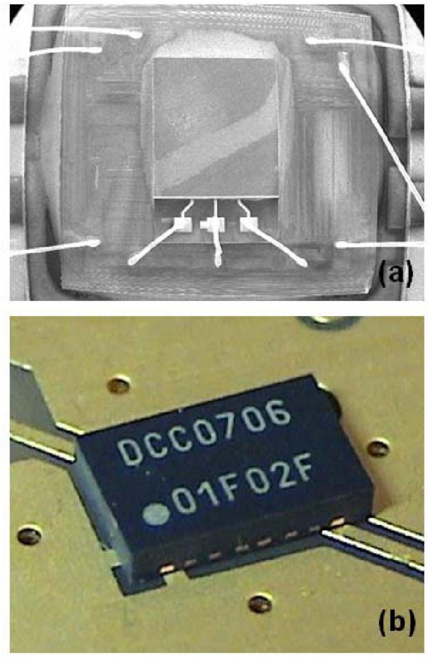

Figure 7 (a) Assembly diagram of a MEMS resonator on top of an oscillator circuit, (b) MEMS oscillator enclosed in a footprint compatible QFN package

various flip-chip assembly schemes for system-in-package (SIP) applications.

Figure 7(a) shows the assembly diagram of a MEMS resonator on top of an oscillator circuit. Unlike quartz crystal oscillators, batch processing semiconductor technologies are used for MEMS manufacturing so that the MEMS resonators have been encapsulated at wafer level in foundries. Therefore, no further hermetic package at assembly level is required for protecting the vibrating element. This fact provides two of the most important advantages for MEMS oscillators: low cost and integration. The IC underneath the MEMS resonator could be digital signal processors, synthesizers, or any other system chips that need a timing source. Figure 7(b) shows both MEMS and IC are enclosed in a QFN package.

One of the biggest challenges of making a MEMS oscillator is the temperature compensation. Silicon resonators

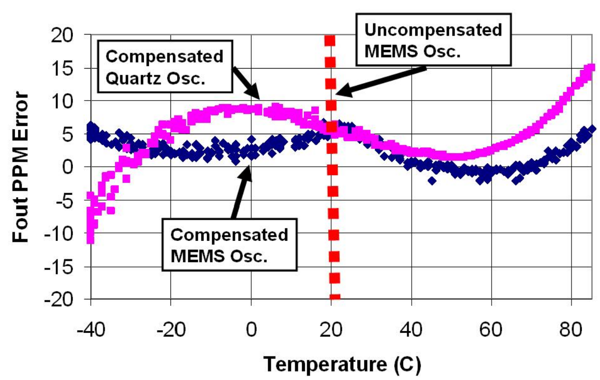

Figure 8 Frequency variations across the temperature of an uncompensated MEMS oscillator, a compensated MEMS oscillator, and a quartz crystal oscillator

typically exhibit monotonic temperature dependent curve. This temperature dependence is mainly due to the temperature coefficient of Young's modulus of the resonator material. As a result, depending on the resonator material, the temperature coefficients range from –20ppm/°C to –40ppm/°C: much larger TC_f than that of quartz. However, the good news is, according to experimental results, the TC_f of the MEMS resonator can be maintained as a straight line from –180°C to 150°C, at least making temperature compensation easier.

Among all the temperature compensation methods [6]-[8], digital temperature compensation through a synthesizer [9] not only gives the most precise compensation, but also provides a way to define the output frequency to the accuracy of 1ppm. Figure 8 compares the frequency variation across the temperature of an uncompensated MEMS oscillator, a compensated MEMS oscillator and a commercial available XO (SG-8002). As shown, uncompensated MEMS oscillator shows TC_f of –20ppm/°C. On the other hand, quartz crystal oscillator is showing typical parabolic characteristics. By applying the digital compensation technology mentioned above, the frequency only varies less than ±5ppm from –40°C to 85°C, which is better than one of the mostly used XO's in industry.

Table I compares electrical performance of a quartz crystal oscillator. As shown, the current consumption of the MEMS oscillator at 33MHz is 33% lower than that of the quartz crystal oscillators at the same frequency – which is very attractive for portable electronics applications. Both oscillators are also showing very similar performance in terms of rise-fall time, output waveform, as well as jitters – indicating that MEMS oscillator can be a direct replacement for quartz crystal in electronic systems. To prove this, MEMS oscillators are implemented into high-end 3 mega pixel camcorders, as shown in Figure 9(a) and (b). It is a direct replacement without any modifications needed. Figure 9(c) and (d) show the images taken by MEMS enabled camcorders. The quality of the images with is comparable to the camcorders with quartz crystal oscillators.

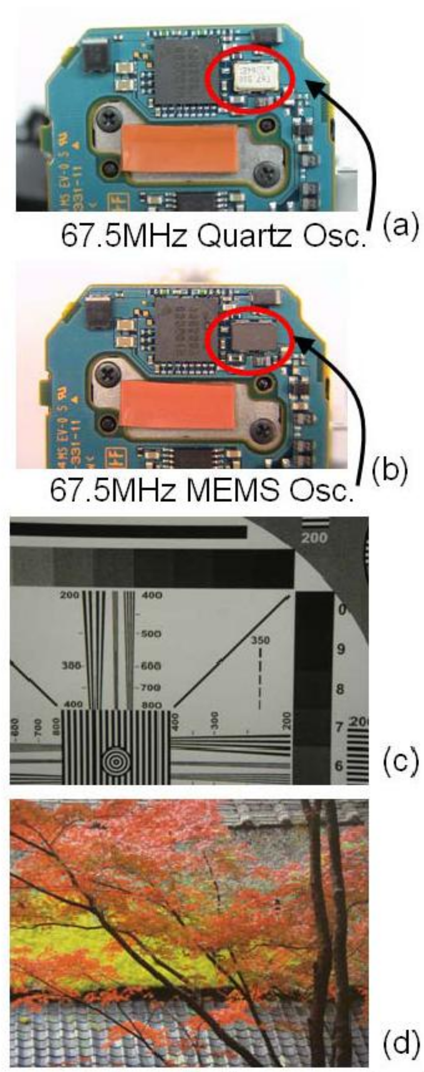

Figure 9 Camcorder head with (a) quartz crystal oscillator (b) MEMS oscillator, (c) and (d) are the images taken by the camcorder with MEMS oscillator (Note: Figure 5(b) is also taken by the camcorder with MEMS oscillator)

MEMS Oscillator Reliability

If a 20MHz resonator vibrates at the amplitude of 100Å peak to peak, the resonator travels 200Å per period, which is equal to 0.4m/s. Over one year, it travels the distance around the earth 3 times. But based on the requirements for electronics, the accuracy of this long trip travel needs to be within 100 meters. Moreover, the change on accuracy can not be tolerated even it travels through desert, tropical forest, or poles. Aging data in [5] have shown that the MEMS oscillator is fully qualified for ±5ppm of aging.

Several tests were completed for packaging reliability. These tests were conducted mainly to identify package or assembly related failures after an accelerated test. The accelerated conditions include moisture soak at 121°C, preconditioning at 125°C, autoclave (note: this autoclave is whole package autoclave. MEMS resonators have been enclosed in the plastic or ceramic packages), liquid thermal shock between –55°C and +125°C. These conditions are based on JEDEC standards and are listed in Table II. As shown in the last column, all packaged MEMS oscillators have passed the screening test.

Furthermore, Cross sectional Scanning Acoustic Microscopy (C-SAM) was used to check the stress variation before and after the tests. Typically, if the change is larger than >10% on the image, it indicates delamination between interfaces. CSAM is taken on before and after all the tests performed. Images before and after –55°C to 125°C thermal shock is shown in Figure 10 as an example. No such variation was found after this probably the most severe stress condition on the package. Moreover, the oscillator output frequency stays in specification after thermal shock.

Some more extremely reliability tests were conducted with MEMS oscillators. MEMS oscillators were tested under military standards on shock resistant at 30,000G, operation vibration at 50G, and constant acceleration at 25,000G [5]. MEMS oscillators have great advantages in these extreme mechanical conditions simply because the mass of the

Table II Package reliability tests and their conditions

Tests	Condition	Passed / Total
Moisture Soak (rejects)	Bake 125° C for 24 hrs @at 121° C / 100%RH for 2 Hours	30/30
Pre-CSAM (soak)	CSAM 50 MHz transducer for plastic	30/30
Pre-condition	24 HOURS BAKE @ 125C 85/85 for 168 hours 3IR @ Lead Free temp. (260-5/+0 C)	203/203
Test after pre-condition	Measure Idd, fref@ 25C	203/203
Pre/Post Autoclave CSAM	Autoclave- 15PSIG/121Csteam, 100%rh t=96hrs CSAM 50 MHz transducer for plastic	9/9
Test after Autoclave	Measure Idd, fref@ 25C	123/123
Pre/Post Th. Shock CSAM	Thermal Shock -55 (+0/-10) deg C to 125 (+10/-0) deg C.100cycles CSAM 50 MHz transducer for plastic	9/9
Test after Thermal Shock	Measure Idd, fref@ 25C	79/79

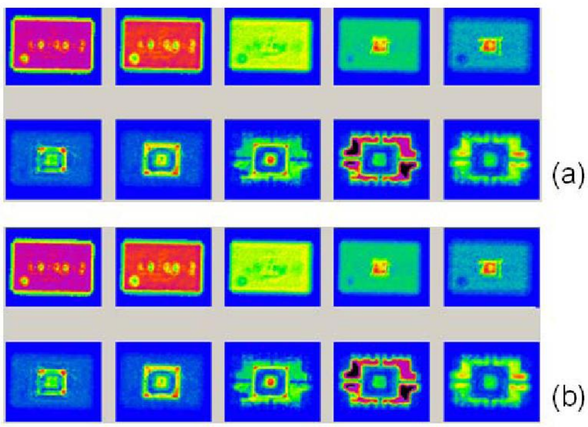

Figure 10 CSAM images of plastic packages (a) before and (b) after –55°C~125°C thermal shock

resonator is very small. This fact enables MEMS oscillators for harsh environment applications.

Conclusions

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 next application target for MEMS oscillators is to reach the accuracy requirements of TCXO for RF applications. Three requirements are needed: (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.

With the development efforts among universities and industry, the MEMS oscillator is getting closer to RF applications. The good news is, due to the reduction trend of cost and size, RF system designers are tweaking system specifications to use low-cost (meaning lower frequency accuracy) and integrated frequency reference sources. As MEMS oscillator researchers are trying to bring up the accuracy, system designers are bringing down the system requirements. We believe, in the near future, that these two specs will merge together.

Promise of CMOS MEMS resonators has been immense for a long time. Finally, technology is commercially viable, and being rolled out as we speak. These MEMS oscillators provide opportunities to change traditional timing devices that people are used to for decades. With the advantages of low cost, low power, high reliability, and integration, MEMS oscillators will grow and evolve over time. Quartz Crystal technology is very important and relevant, and will continue to have its unique share of the market, though over time this share may probably be on the decline.

Acknowledgments

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